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Development of a Micro-shot Peening Process and Testing of Micro-shot Peened Engineering Materials

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Declaration

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Signature James Vahey Date 12/10/2006

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Abstract

A precision, air blast, shot peening machine was designed and developed and used to carry out peening operations on engineering materials and components. The machine was designed to allow all the variables of the peening process to be controlled and adjusted. The micro-shot peening process was applied to a series of standard High Speed Steel twist drills, carbide inserts for milling cutters, turning tools and EPDM material.

The drills were used under controlled CNC conditions to machine mild steel plates. The useful cutting life of the drills was monitored. The surface finish and the dimensional accuracy of the holes were also recorded. Identical tests were performed using standard unpeened drills. The results from the cutting performance of the peeened and unpeened drills were recorded and compared. Similar peening operations were applied to carbide inserts for milling and turning tools and the performance of the peened tips was compared with unpeened tips. The application of micro-shot peening to standard cutting tools was evaluated. From the research work conducted, micro-shot peening is proved to be a useful process in improving the life of cutting tools.

Tests carried out on EPDM material showed that the surface texture was improved by micro shot peening but no improvement was achieved in its tensile or fatigue properties.

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Chapter 1

Introduction

1.0 Introduction

Micro-shot blasting or micro shot peening is a cold working process, which involves the bombardment of the material surface using minute spherical projectiles as shown in Figure 1. The projectiles are referred to as shot. The shot is directed onto the surface of the material at high velocity using such methods as a compressed air blast or by centrifugal force from a rotating wheel. These two methods are referred to as conventional shot peening. The material used for the shot depends on the application of the process and may vary from relatively soft steel shot to extremely hard ceramic material. The size of the shot can vary from 100 microns to 10mm depending on the application of the process. In micro shot peening the diameter of the shot would be less than 1mm.

The energy due to the deceleration of the shot at the point of impact is dissipated in four ways:

i Plastic deformation of the material.

ii Elastic deformation of the material.

iii Rebound of the shot.

iv Production of heat.

Estimates have been given that up to 90% of the energy is transferred to the material [1]

The plastic deformation of the material at the point of impact is the basis for the shot peening process [2][3]. Small craters are formed at the point of each impact and the original surface of a peened component will be completely obliterated by these craters. The material in the crater zone will be in a state of residual compressive stress as described in section 1.1. Since the entire surface is covered in craters it will be in a state of compressive stress.

Shot Peening

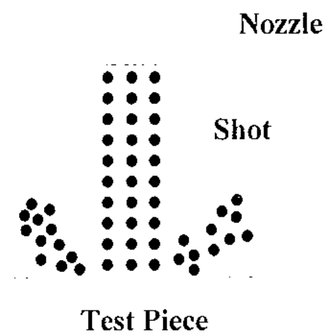


Figure 1. Shot Peening Process

1.1 Effects of Shot Peening

The mechanical and physical properties of the material surface will undergo changes as a result of this process. [2] The main mechanical properties which are changed by shot peening are:

i Type of stresses at the material surface.

ii Micro-hardness of the material.

iii Surface finish

The type of stress at the material surface is the primary concern in shot peening as this process produces a residual compressive stress in any peened surface [2] [3]. This is due to the plastic deformation that occurs as a result of the impact energy of collision between the shot and the material surface as shown in Figure 2.

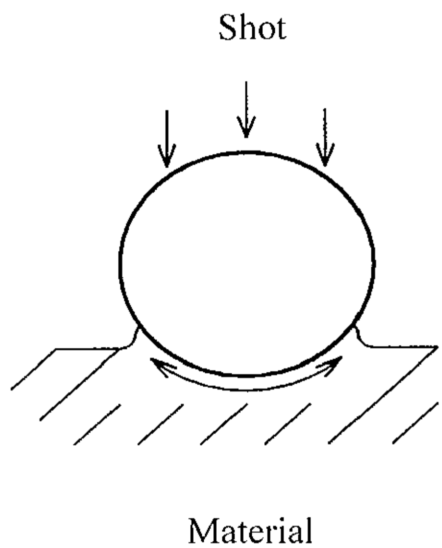


Figure 2. Plastic deformation of material.

When a collision occurs between a spherical indenter and a surface both the indenter and the surface will deform elastically according to the classical equations of Hertz. The region of contact is a circle of radius a as shown in Figure 3.

Figure 3. Region of contact between indenter and material.

The radius a is given by the equation

$$a = \left\{ \tfrac{3}{4}\, Wgr \left(\frac{1-\sigma_1^2}{E_1} + \frac{1-\sigma_2^2}{E_2} \right) \right\}^{1/3} \qquad [4]$$

where W is the force applied, E_1 and E_2 are Young's moduli for the indenter and the indented metal respectively, and σ_1 and σ_2 are the corresponding values for Poisson's ratio. Since Poisson's ratio has a value of approximately 0.3 for most metals, this gives

$$a = 1.1 \left\{ \frac{Wgr}{2} \left(\frac{1}{E_1} + \frac{1}{E_2} \right) \right\}^{\frac{1}{3}} \qquad [4]$$

Therefore the projected area A of the indentation is proportional to $W^{\frac{2}{3}}$ and the mean pressure P over the region is proportional to $W^{\frac{1}{3}}$. The pressure across the circle of contact is not uniform, but at any point of distance x from the centre of the indentation has a value $P = P_0 (1 - x^2/a^2)^{\frac{1}{2}}$ where P_0 is the pressure at the centre of the circle.

Therefore $P_0 = \frac{3}{2} P_m$.

If the Tresca or the Huber- Mises criterion are applied to the stresses in the metal it is found that the condition for plasticity is first reached at a point below the actual surface of contact as shown in Figure 4. When the calculated shear stress in the metal is plotted it is found that maximum value occurs at $0.5a$ below the centre of the region of contact. The value of the shear stress at this point depends on the value of Poison's ratio but for most materials for which Poisson's ratio is 0.3 the value is $0.47P_m$, where P_m is the mean pressure over the region of contact. Since at this point the two radial stresses are equal, the Tresca and Huber-Mises criterion both indicate that plastic flow will occur when the shear stress equals 0.5Y. This means that plastic deformation will occur when $P_m = 1.1Y$. [4]

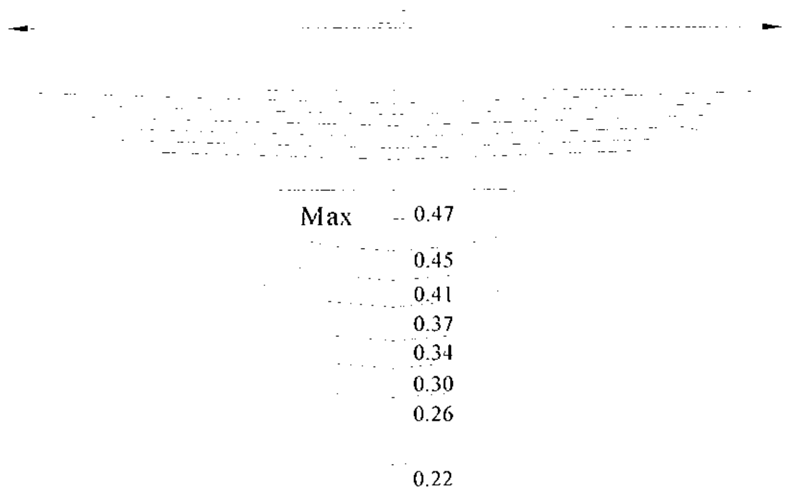


Fig 4 . Elastic deformation of a flat surface by a sphere showing the max shear stress in the bulk material [4].

After the impact there will be a compression zone at the point of impact because the plastically deformed material is unable to expand due to the restraint imposed by the surrounding material as shown in Figure 5.

Figure 5. Compression Zone After Impact [2].

When this operation is carried out on the surface of a part, the compression zones will occupy the entire surface. This results in a residual stress layer as shown in Figure 6. The depth of this layer is normally 0.2mm for conventional shot peening but can extend to a depth of 1mm for other methods as discussed in section 2.6 [2]. The type of stress, tensile or compressive, that exists at the surface of a material has a significant influence on the service life and performance of engineering components as described in section 2.0. [2]

Shot Peened Part

Compressive Stress Layer

Unaffected Layer

Figure 6. Compressive Stress Layer

The micro-hardness of the surface is increased and this is a useful side effect of the shot peening process in applications where surface wear is encountered, such as cutting tools. [5]

Shot peening also changes the physical properties of the material surface, such as the surface texture and the porosity. The surface texture usually suffers a disimprovement but this can be used advantageously in some engineering applications where lubrication retention is an important consideration. Electro-polishing, which involves the electro-chemical removal of the surface layer, may be carried out after peening to obtain a specific surface texture. Some surface textures can be improved by the application of the shot peening process. Porosity at the surface of materials is reduced or eliminated by shot peening. In this case plastic flow of material, due to impact of the shot, will occur to fill any voids that are present at or near the surface of the material. [2].

The early work of this process was mainly concerned with improving the surface stiffness of the material as properties such as fatigue resistance, surface texture and surface micro-hardness were not the vital factors that they are in modern engineering [2]. The beneficial effects of shot peening as a production method were first realized about 70 years ago and over the intervening years many improvements have been made in all of the variables of this process. With modern process control it is possible to achieve beneficial modifications to the surface properties of materials by shot peening with a high degree of repeatability and reliability. This results in extended life and improved performance of components. [2] It is also possible to modify the shape of material to produce three-dimensional shapes from flat plate as discussed in section 1.2 [6]

1.2 Applications of Shot Peening

Shot peening is used in four broad areas of engineering [6].

i. Removal of surface imperfections, which are present as a result of previous operations or processes. These imperfections include machining marks, burrs, welding slag deposits, rust and oxidation due to heat treatment. The removal of these imperfections results in an improved appearance of the component. It also results in a reduction in the number and level of stress raisers, which are features on the surface where stress levels are increased.

ii. Surface profiling which causes a roughening of the surface texture. This produces a superior bonding surface for subsequent protective surface treatments such as painting or protective metal coating.

iii. Improvement of mechanical and physical properties. The properties which are enhanced by this process include the following:

(a) Fatigue life. Fatigue is a mode of failure of components that are subjected to cyclic stresses in service as described in 2.2. The components fail at a stress level well below the ultimate tensile strength. A contributing factor to fatigue failure is tensile stress that is necessary for the propagation of fatigue cracks. Since shot peening produces residual compressive stress this offsets the tensile stress that is present in cyclically loaded components. This extends the service life of components.[2][15]

(b) Stress corrosion resistance. Stress corrosion is a mode of failure that occurs in susceptible alloys that are subject to static tensile stress and operate in corrosive environments as described in 2.3 The residual compressive stress induced by shot peening effectively removes one of the three conditions necessary for this mode of failure, e.g. tensile stress. [2] [9] [10]

(c) Wear resistance. As the micro-hardness of the surface is increased by shot peening its resistance to wear is also increased.[5]

iv. Peen Forming. In this operation large structures such as the fuselage and wing casings for aircraft can be formed into the required shapes by selectively peening the flat plates from which these components are manufactured. Wing surfaces for aircraft such as the Airbus 330 are manufactured by this process.[2] An extension of this process is the correction of distortion in components as a result of machining or heat treatment. Selective peening at critical points on the internal and external surfaces of cylinders can be used to correct the problem of bore ovality. This operation is used extensively on automobile connecting rods for correction of bore ovality at the rod "big end"[2].

1.3 Focus of Thesis

The main objective of this thesis was to study the effects of shot peening, under controlled conditions, on the mechanical properties of engineering materials. To carry out this study it was necessary to become conversant with all the current aspects of shot peening. It was also necessary to design and manufacture a dedicated machine, which allowed the shot peening process to be applied to components and test pieces. This machine enabled the many variables of shot peening to be controlled and varied during the tests. Tests on a wide range of engineering materials, both metallic and non-metallic, were carried out in addition to experimentation on the variables of the process. The residual compressive stress layer induced in the material as a result of shot peening was closely examined. Determination of the compressive stress value and its depth from the material surface formed part of the study. An assessment of surface texture was also performed. Cutting tools and carbide tips for cutting tools were shot peened. The tools were then be subjected to normal cutting operations under controlled conditions. The performance of these tools, such as tool life, cutting forces and the quality of the surfaces produced on components, were then compared with the performance of identical tools that had not been shot peened. The results of these tests and conclusions derived from the results form a large part of the thesis.

Shot peening was carried out on non- metallic materials to determine if the mechanical properties were modified by this process. Tensile tests, fatigue tests, hardness tests and surface texture assessment were carried out on peened and unpeened samples of selected materials.

1.4 Aims and Objectives

1.4.1 Aims.

The main aims of this research were;

i. To perform a series of experiments using the process of shot peening to determine if further improvements to the properties of metallic materials could be achieved by the optimisation of the variables of the process.

ii. To perform a series of experiments using the process of shot peening on non-metallic materials to determine the effects of the process on the properties of these materials.

1.4.2 Objectives

The main objectives of this research work were;

i. To carry out a detailed literature survey on the subject of shot peening.

ii. To determine the variables of the process.

iii. To design and build a shot peening machine which would allow the variables of the shot peening process to be adjusted and controlled.

iv. To perform a series of experiments using the process of shot peening on a number of Almen strips to determine the optimum values for the variables of the system.

v. To perform a series of experiments using the process of shot peening on a variety of materials to determine the improvements, if any, that result from the application of this process.

vi. To analyse the results of these experiments.

vii. To derive conclusions and recommend further work.

Chapter 2
Development of Shot Peening

2.0 Development of Shot Peening

Peening or cold hammering of metal to improve its properties is a traditional metalworking process. Metal craftsmen painstakingly peened jewellery, ornaments and cooking utensils to produce decorative effects. Peening was also carried out on, tools and weapons to produce what was then considered to be the optimum properties in the material [11].

The first developments in projectile shot peening were carried out by Herbert in 1927 when he devised equipment for projecting steel balls onto metal surfaces to bring about improvements in the hardness of the metal [12]. Other improvements resulting from this process were not mentioned or recognised in his work

Weibel in 1935 found that this process improved the life of coil and leaf springs and this was the first reference to peening bringing about an improvement of fatigue life [11].

Zimmerli carried out tests in 1940 on the improvement in the fatigue fracture life of peened torsion springs [13]. His experiments showed that the fatigue life of the springs were increased substantially by peening but that peening times above 10 minutes did not produce further improvement. This implied a saturation factor for the process. His studies also showed that annealing a material after peening reduced or eliminated any improvements induced by the process.

The extension of the peening process to machined parts was pioneered by Almen in 1943 who observed that some finishing processes, such as grinding, produced micro cracking of the material surface [14]. This was attributed to the heat generated by the abrasive finishing operation. The micro cracking was also accompanied by tensile stresses, which is a condition in which fatigue cracks can be easily initiated and propagated.[22] Almen showed that the substitution of abrasive finishing with peened finishing eliminated surface cracking and replaced the tensile surface stress with a compressive stress at the surface.[14] The benefits of these changes are considerable as it is a well established fact that fatigue cracks will not initiate in or propagate through compressively stressed areas.[18] [22] Since nearly all fatigue and stress corrosions failures originate at or near the surface of a component, compressive stresses induced by shot peening provide significant increases in component life.[15] Almen also developed the Almen strip, which is still used today for determining the intensity level of shot peening [20].

In 1945, Milburn applied the principle of X ray diffraction, to peened surfaces to determine the magnitude of the compressive stress in the surface layer [11]. In 1946 H.O. Fuchs and R.L. Matson undertook an investigation into the effects of shot peening and the resultant residual stresses induced in torsion bars [11]. Gould and Evans discovered in 1948 that shot peened parts showed increased resistance to corrosion fatigue [11]. In 1959, an analysis of residual stress states induced by shot peening was carried out by Mattson and Roberts [11]. The stress peening process was developed in 1949 by J. C. Straub and D. May. [11] This involved the peening of the part while it was stressed by the application of an external force. The applied stress was in the same direction as that encountered in the service life of the part. This process showed improved results from that achieved by shot peening without the application of an external force [11].

There has been further substantial research carried out on this subject over the past fifty five years mainly in the automotive and aeronautical industries, where reliability and weight of components are crucial factors [25] [30] [32]. Results show that correct peening can produce many beneficial effects in material properties and consequent extension of component life [15]. A number of applications of shot peening in the automotive industry where substantial gains in component performance were achieved are shown in Table 1. [15]

Component	**Percentage Increase in Life**
Steering Knuckles	475%
Leaf Springs	600%
Crankshafts	900%
Connecting Rods	1000%
Coil Springs	1370%
Rocker Arms	1400%
Gears	1500%

Table 1. Improvement due to shot peening.

Peening also enables lighter components to be used without compromising on strength or reliability [2]. New methods of applying the process have been explored and developed [2]. The effects of temperature and time on the process continue to be studied at the present time .

2.1 Benefits of Shot Peening

Shot peening of components produces several beneficial results.

One of the most important beneficial effects of peening is the increase in the useful life of components that are subjected to cyclic stresses [11] [12] [13][14] [15]. Fracture of components as a result of these types of stresses is referred to as fatigue failure. Another important beneficial effect of the process is an increased resistance to stress corrosion cracking [9] [10]. This form of failure occurs in aggressive environments where static tensile stresses are present in susceptible metals and alloys.

A side effect of peening is the change in surface texture. This is dependent on the hardness of both the peening media and the material being processed. The correct combination of these parameters can produce surface textures that are suited to different service requirements.

2.2 Fatigue Failure

Fatigue failure cracks usually begin at the surface of components in minute cracks or surface imperfections and are propagated by tensile stresses until the crack is of sufficient magnitude to cause critical weakening of the component. The component will then be unable to resist the normal torsional or tensile forces that are applied and total fracture will occur [22]. Increases of up to 1500% in the fatigue life of components may be achieved by the correct use of shot peening [15]. This is due to the two main effects of peening;

i. The closure of micro-cracks on the surface of components, which can be the source of crack initiation [22].

ii. The development of a surface, which has a residual compressive stress. As fatigue is propagated by tensile stresses, the residual compressive stress of the peened surface tends to resist crack propagation [22].

Figure 7 shows a typical S/N curve for a steel component [22].

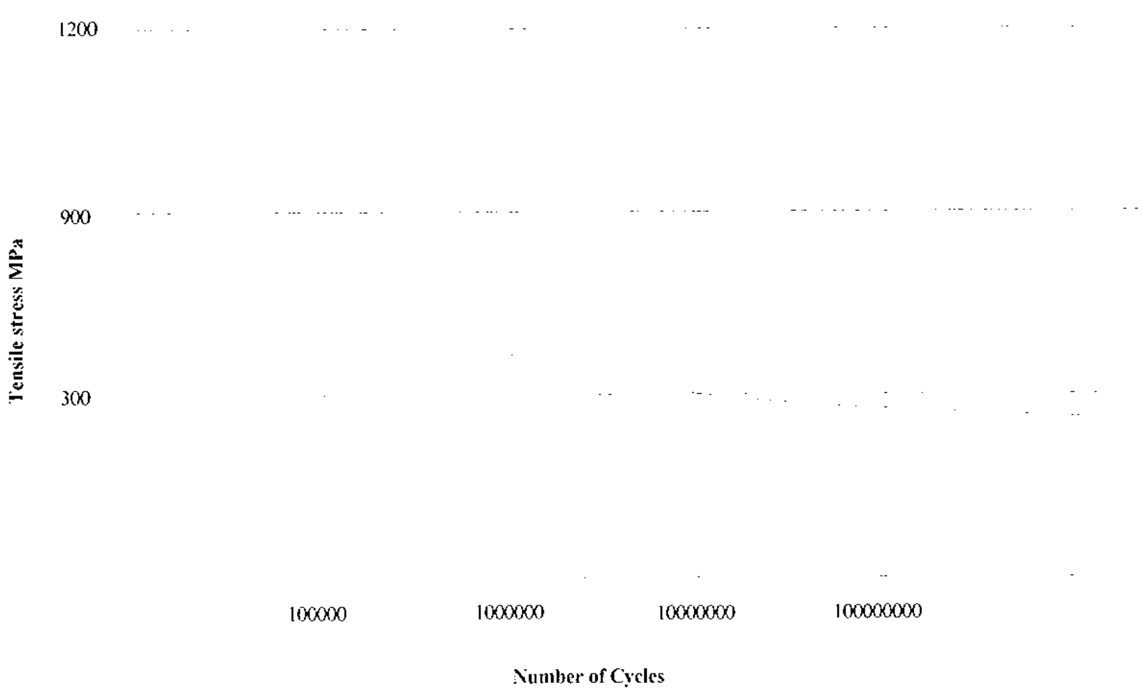


Figure 7. S/N Curve for steel.

This shows the number of cycles a component can withstand before failure at a given level of stress. The component life, the number of stress reversals it can withstand before failure, is determined by the magnitude of the tensile stress. By reducing this stress, or counteracting the tensile stress by inducing a compressive residual stress, the life of the component can be extended by up to 1500%.[15] Shot peening is used extensively on metallic parts that have to withstand this type of cyclic loading in service.

The following benefits of shot peening, with regard to fatigue life, were summarised by Fuchs as long ago as 1963 [18].

i. Parts with section changes or other stress raisers can benefit more by shot peening than parts that are smooth.

ii. Parts with skins that are prone to fatigue damage, (decarburization, corrosion attack, chromium plate) can gain far more than parts without such skins.

iii. Potential gains in fatigue life increase with the hardness of the steel, regardless of alloy content. At equal hardness levels, various steel alloys gain about equally.

iv. If failures occur at less than 1000 cycles, shot peening is not likely to be beneficial. If failures occur at more than 100,000 cycles, shot peening is likely to increase the life by a large factor.

v. Large and small parts can gain equally by peening.

vi. Occasional high tensile loads, such as many components experience in service, will reduce the beneficial effects of peening.

Although Fuchs referred only to steels, shot peening is now used to improve the fatigue performance of a much wider range of ferrous alloys, non-ferrous metals and non-ferrous alloys [2].

2.3 Stress Corrosion Cracking

Stress corrosion cracking is a progressive fracture mechanism in metals that is caused by the simultaneous interaction of corrosion and sustained tensile stress [9] [19].

Virtually all alloys are susceptible to stress corrosion cracking, which may occur suddenly and is difficult to predict. For stress corrosion cracking to occur, it is necessary for three adverse conditions to exist in or surrounding the component. These conditions are susceptible metal, corrosive environment and static stress. The tensile stresses necessary for stress corrosion cracking are static and may be residual or applied. The residual stress may be present from manufacturing processes while the applied stress may result from assembly methods or external forces.

Compressive stresses, such as those induced in the surface layers of a component by shot peening, can be used to offset the tensile stress element thereby eliminating one of the conditions necessary for this mode of failure. Provided this compressive layer remains and is not relaxed thermally or by excessive tensile stresses it will protect the component or structure against failure by stress corrosion cracking.

2.4 Surface Finish

The surfaces of manufactured components will all deviate to some extent from absolute perfection. The extent of these deviations will depend to a large degree on the production method employed in the manufacture of the component. The quality of the surface finish can have an influence on the performance of the component in such areas as fatigue life, wear resistance, bearing properties and functional interchangeability. In practice the imperfections on a surface take the form of a series of peaks and valleys which may vary in height and spacing to produce a distinct texture. The texture is often recognizable as that produced by a particular manufacturing method. The imperfections on the surface will consist of two main facets of departure from perfection, waviness and roughness. [31]

Waviness is a long wave departure from the intended surface and is due to machine deflections, vibration, heat treatment or warping strains.

Roughness is a short wave departure from the intended surface and is superimposed on the waviness feature. This form of irregularity is due to the inherent properties of the production process. The roughness of a surface in many cases will have a predominant direction and this is known as lay. The direction of lay will be determined by the manufacturing process.

Figure 8 shows a typical machined surface that contains waviness and roughness.

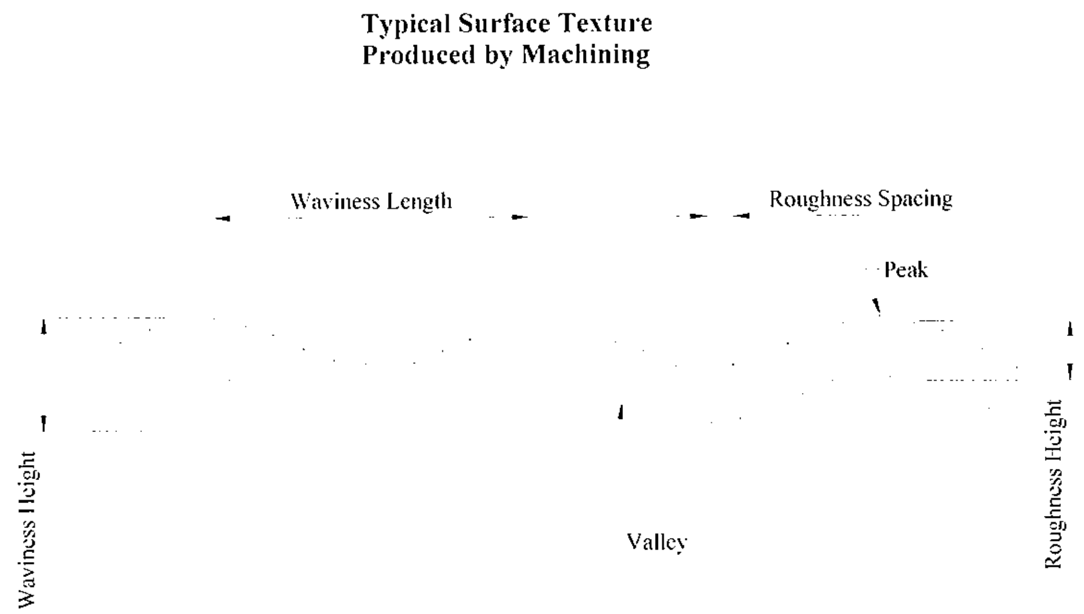


Figure 8. Surface with Waviness and Roughness. [31]

The roughness of a surface may be quantified by measurement using a stylus type instrument which is moved across a sample length of the surface in a straight line. The readings obtained are for the short wave deviations only which give a peak to valley based reading which is a measure of roughness.

A number of peak to valley standards are used but the most commonly used standard is Ra. This is defined as follows: Ra = Arithmetic mean deviation. This is calculated by taking the sum of the peak and valley areas above and below a line drawn through a trace of the surface. This sum is then divided by the length of the trace giving the average height deviation about the mean line.

Reducing the roughness of a component surface produces many beneficial effects which enhance the performance and prolong service life in many instances.

The closure of micro cracks or the elimination of minor imperfections on the rake face of cutting tools can contribute to the life and performance of the tool. Tool failure usually occurs at two locations on the tool. [23]

i. Wear at the chip/tool interface, which is referred to as crater wear.

ii. Wear at the work/tool interface, which is referred to as flank wear.

The onset of both of these conditions can be delayed by the application of peening, resulting in an extended tool life [5]. This is due to an improvement in the surface finish on the tool rake face and the tool flank. Better conditions then exist for sliding of the chip over the rake face of the tool. The improved condition of the tool flank, which is nominally in contact with the work piece finished surface, also incurs less wear. Figure 9 shows a machined surface which is shot peened. The peaks on the surface have been plastically deformed thereby reducing the Ra value. Cutting forces are also reduced which results in lower running costs and higher production rates. In addition the resulting surface finish of the machined component will show a distinct improvement when produced by peened cutting tools [5].

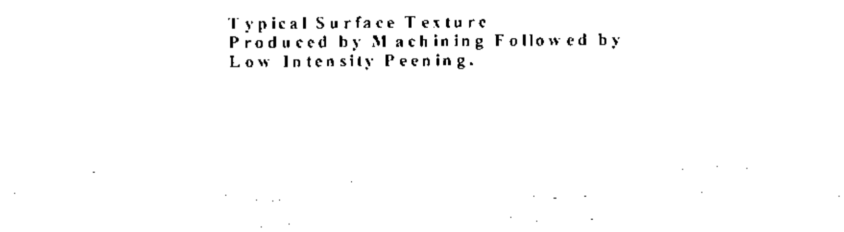


Figure 9. Shot Peened Surface with Reduced Roughness. [5]

2.5 The Peening Process.

When a surface is peened the material is bombarded with projectiles travelling at velocities of up to 80 metres per second. The material will be elastically or plastically deformed due to the impact energy of the individual projectiles. If the yield point of the material is exceeded by a factor of 10% then permanent deformation will take place at the point of impact on the surface [4]. As the surface is subjected to multiple impacts due to the shot stream, the entire surface area exposed to peening will undergo permanent deformation. The amount and depth of the deformation may be quiet small, depending on the shot size and velocity, but the result will be a small increase in the length of the grains in the surface layer of the material. The depth of the compressive layer, which results from the deformation, will depend on the intensity of the peening operation but can extend to a depth of 0.2mm below the peened surface for conventional shot peening [2] and to a depth of 1mm below the peened surface for laser shock peening as described in section 5.2. The material layer under the plastically deformed layer will be unaffected by the peening operation and will retain its elasticity. The material in the outer layer will be much stronger in tension and compression than the unaffected layers underneath. Since the grains in the peened layer are bonded to the grains in the unaffected layer there will be an equilibrium condition between the two layers. If the material thickness is small, less than 2mm, the stress in the compressive layer may be sufficient to overcome the tensile stresses in the unaffected layer. In this case the material will be deformed. The previously flat material will now be in the form of a section of a spherical surface. If the material is of substantial thickness there will be a compressive stress at the surface, which is counteracted by a tensile stress in the unaffected layer. The tensile stress in the unaffected layer will force the elongated grains of the peened layer to remain at a shorter length than if they were unrestrained. This results in a residual compressive stress in the peened surface layer of the material. The level of compressive stress induced will depend on the initial tensile strength of the material and the intensity of the peening operation. The maximum residual compressive stress occurs some distance below the surface and decreases to zero at a depth of 0.2mm for conventional shot peening as shown in Figure 10. [2].

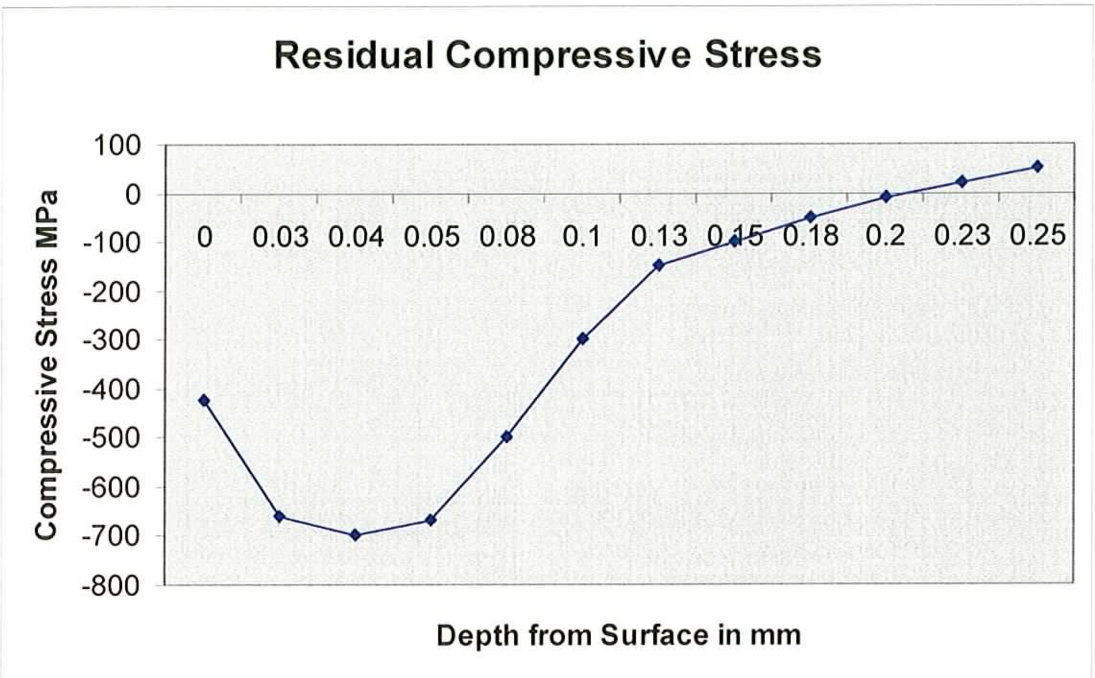


Figure 10. Depth Profile of Compressive Stress [2]

Peening results in a residual stress in the material, which is a stress system that exists where no external force is applied as shown in Figure 11(a). When an external force is applied the residual stress and the applied stress are added together to give a resultant stress as shown in Figure 11(b).

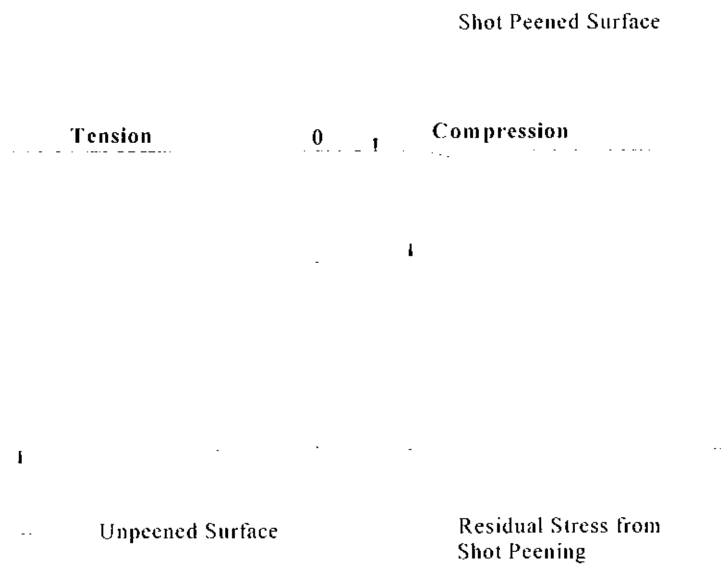


Figure 11a. Residual Compressive Stress. [2].

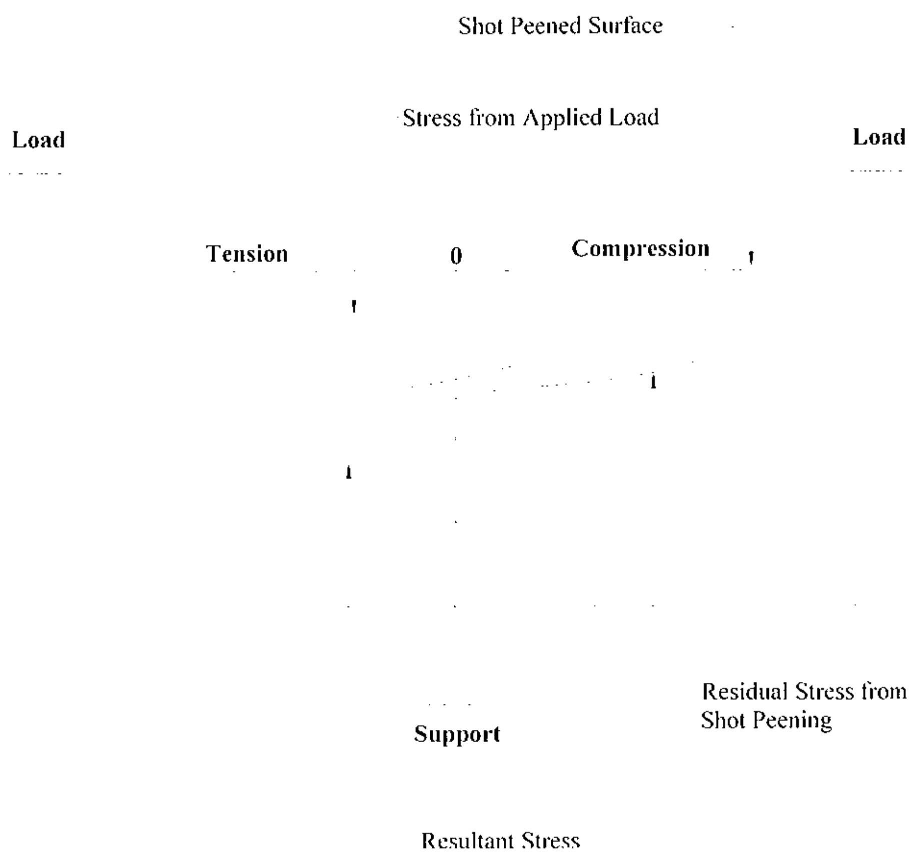


Figure 11b. Residual Compressive Stress And Applied Load. [2].

The effect of strip distortion was used by J. O. Almen, who carried out extensive research work on peening, to measure the intensity of peening operations. The Almen strip, developed by J. O. Almen, is now used as a standard test for intensity in peening operations [20].

Commercial peening operations involve the bombardment of a surface by spherical projectiles. These projectiles may be impelled onto the surface by a high velocity stream of compressed air, by water jet or by the centrifugal force produced by a rotating wheel, (wheelapeening) [8]

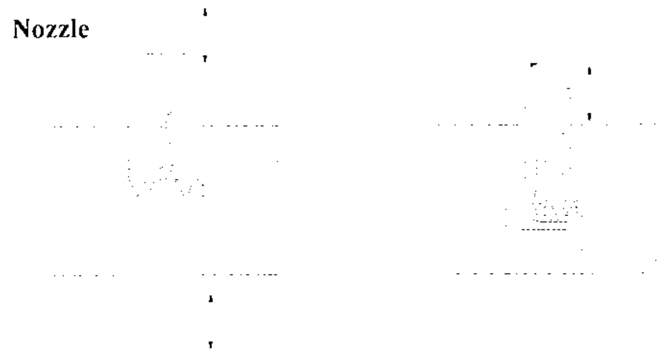
Peened surfaces possess a high residual compressively stressed outer layer that is covered in minute craters. For some engineering applications this type of surface texture may not be ideal. Some of this cratering can be removed by a subsequent operation without excessive loss of the beneficial compressive layer. The peening process is very versatile in that it can be applied to any external surface of a component regardless of the complexity of its shape.

Internal surfaces and bores can also be shot peened if they are capable of being accessed by the shot delivery nozzle [24]. If the hole diameter is greater than the hole depth it can be peened using a normal direct pressure nozzle inclined at 45 degrees to the hole axis as shown in Figure 12(a). If the hole depth is up to twice the diameter and is open at both ends, it can be peened using two normal direct pressure nozzles as shown in Figure 12(b). The nozzles deliver shot through the top and bottom of the hole and are inclined at 45 degrees to the hole axis.

(a) Direct Pressure Nozzle

(b) Two Direct Pressure Nozzles

Figure 12. Internal Peening. [24]



(a) Reciprocating Shot Deflector (b) Reciprocating and Rotating Peening Lance

Figure 13. Internal Peening [24].

For deeper holes it is necessary to use a reciprocating shot deflector as shown in Figure 13(a), or a rotary reciprocating peening lance as shown in Figure 13(b). The minimum bore that can be peened using current technology is 2mm diameter [24]. Internal surfaces can also be shot peened using a variation of the conventional process called ultrasonic shot peening.

2.6 Ultrasonic Shot Peening

In this process, a limited quantity of shot is placed in a container, which holds the component to be shot peened. The component is mounted in such a manner that the surfaces to be treated are fully exposed to the shot. The entire assembly is placed on a sonotrode, which produces vibrations of frequency

20KHz and amplitude of 0.09mm. The shot particles, moving at high velocity, impinge on the surface of the component in a manner similar to conventional peening, thereby inducing a residual compressive stress [2] The main advantage of this method is the limited quantity of media required and the environmentally friendly nature of the totally enclosed process. Hollow components can be shot peened on their inner surfaces by this method provided that the shot can be inserted into the cavity and removed when the peening operation is completed. The peening of internal surfaces of components contributes substantially to the performance and life of the component particularly in conditions of cyclic loading [2].

2.7 Laser Shot Peening

Laser shot peening was developed in the 1970s as a laboratory process but is now being used widely as a production process.[2] This process uses laser generated pulses to produce a similar effect to shot impact. Shock pressures of 10^4 to 10^5 bar can be achieved at the metal surface if a tamping layer of suitable material, usually water, contains the shock wave. The metal surface must be coated with a black paint to achieve absorption of the laser beam . Although this process is relatively expensive it does produce results, which show significant improvements over conventional shot peening. The magnitude of the compressive stress is comparable to that of shot peening but two significant improvements are achieved: [2]

i. Greater depths of compressive stress layers are achieved, with typical values up to 1mm.
ii. No craters are produced on the material surface by this method of peening.

2.8 Overview of Micro Peening Process Parameters

Figure 14 shows a typical flow chart for the peening process [20].

Shot mass, shot hardness, shot velocity and impact angle all contribute to the kinetic energy of the shot.

The exposure time and shot flow rate are the two factors which produce the required coverage.

Peening intensity results from the application of kinetic energy in the form of impacts between the shot media and the material surface. Optimum results for the process may be attained by the application of the correct coverage and the correct kinetic energy [20] [37] [38]. The intensity parameter may be determined by the use of a suitable Almen strip. Although this strip is used widely in industry to indicate the peening intensity in the strip and in the component, which is given an identical treatment, it does not quantify the compressive stress in the component surface or the consistency of the treatment over the entire surface of the component. These can only be measured and verified by a series of subsequent tests such as X-rays or strain gauges [26] [33].

Post peening operations such as electro-polishing may be carried out to improve the surface texture without reducing the compressive stress layer by a significant amount.

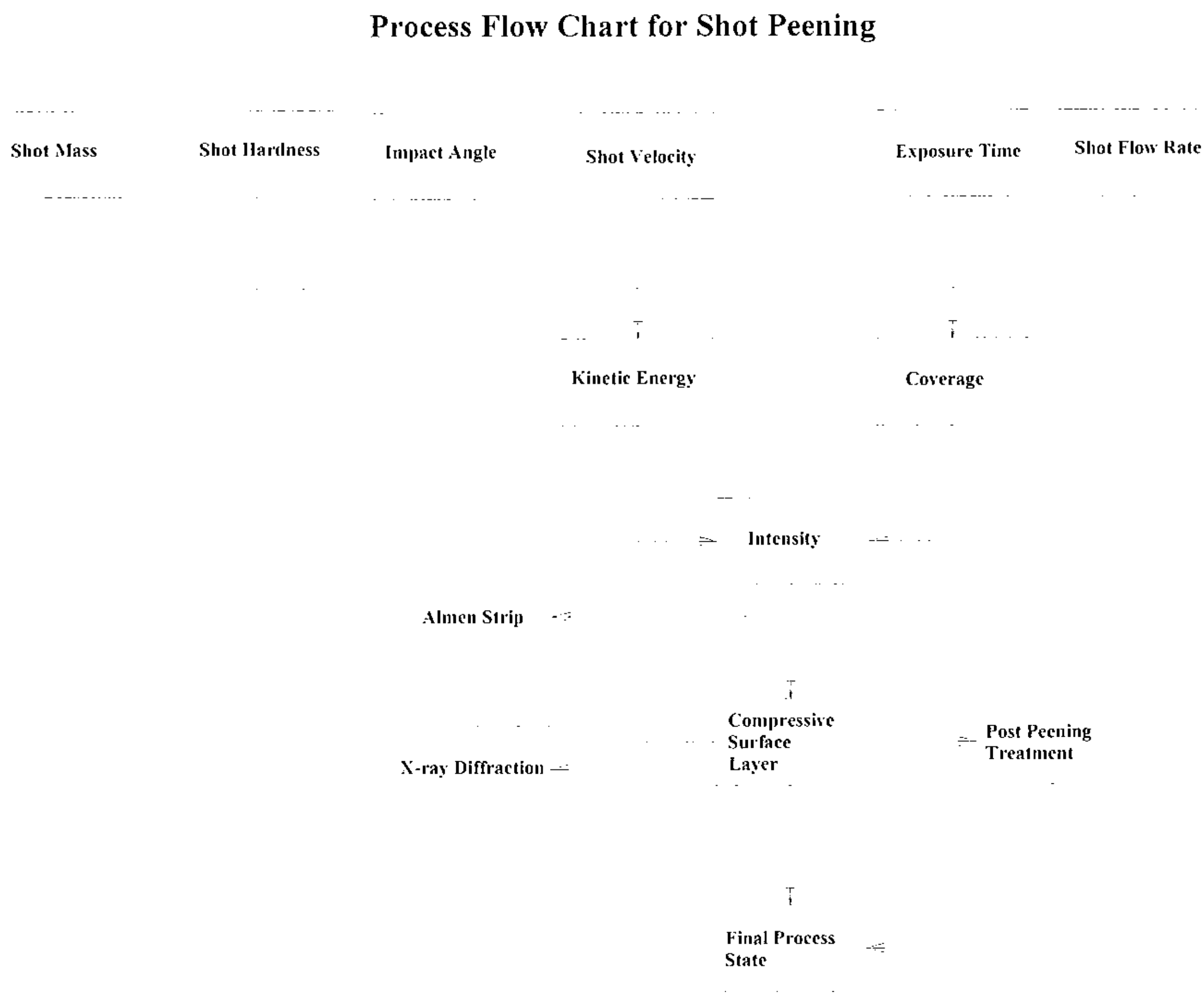


Figure 14. Shot Peening Flow Chart. [20].

2.9 Effects of Temperature on Shot Peening

Recent studies have shown that annealing of the material before shot peening can have significant beneficial effects [10]. The annealing temperature and the duration of the annealing process both influence the effectiveness of subsequent shot peening operations. It is possible to optimize the annealing process for different metals in order to produce optimum results from the shot peening process.

Shot peening at temperatures up to 290 degrees C, which is referred to as warm peening, can result in increases of up to 20% in the fatigue life of components.[25]

The stress relief temperature is a physical property of all metals and varies depending on the melting point of the metal. Stress relief is normally, fully achieved at temperatures of 40% to 50% of the absolute melting temperature [27]. The amount of residual compressive stress that is relieved as a result of exposure to elevated temperatures is a function of the temperature level, the material and the duration of exposure. A material such as Inconel 718, which is used in aircraft engines, has its compressive stress reduced by 50% when exposed to a temperature of 760°C for 100 hours [2]. Other metals are stress relieved at lower temperatures than the above example, therefore the shot peening process may only be applied successfully to components operating at temperatures below the stress relieving temperature for the particular metal. If the operating temperature is excessive the compressive stress layer will be relaxed thereby canceling the effects of shot peening [30].

Chapter 3
Determination of Compressive Stress

3.0 Determination of Compressive Stress Values

There are a number of techniques for measurement of residual stress that are considered theoretically possible but only two have been perfected to the stage where they are in everyday use in industry. These two methods are X-ray diffraction and the hole drilling method [22] [26] [33] [34]. The ability to measure stress gradients along the surface as well as beneath the surface is desirable but difficult to achieve. In most stress tests it is essential that they be of a non-destructive nature. The possible complexity of residual stress patterns in practical components suggests that no single method can meet every test requirement. Sometimes two or more methods may be used to obtain accurate data. Stress conditions within the interior of a part are impossible to measure non-destructively by any presently available method.

3.1 X-ray Diffraction Method

X-ray diffraction technology was used as early as 1912 for the determination of crystal structures but its development for compressive stress measurement did not occur until the early 1960s. Crystallography utilizes the basic concept of a "unit cell", that is the smallest group of repeating atoms of which all crystals are composed. Various families of planes may be drawn through the corners of the unit cells that form a crystallite. Such planes are separated by an interplanar spacing, d.

The angle of diffraction of an X-ray beam is a measure of the interplanar spacing. The diffraction angle, 2θ, is related to the interplanar spacing and the wavelength of the radiation by Bragg's law, i.e. $2d \sin \theta = \lambda$. The X-ray wavelength, λ, is of the order of magnitude of the interplanar spacing, d, approximately one or two Angstroms, (10^{-10} metres). A departure of the interplanar spacing from the unstressed value represents a stress in the material and this is the basis of the X-ray diffraction method for measurement of residual compressive stress as shown in Figure 15 [22]

In accordance with the Poisson effect, the interplanar spacing will elongate in the direction of the applied stress and contract in the transverse direction if a tensile load is applied. It is assumed that the stress normal to the surface is zero. The only possible stresses therefore are biaxial in the plane of the surface. The X-ray beam is usually directed at the surface from at least two different angles, Perpendicular to the surface and at 45 degrees to the surface. If the material is stressed in tension, the X-ray beam normal to the surface will be diffracted by an angle (2θ) that corresponds to the slightly reduced interplanar spacing . The beam projected at 45 degrees will be diffracted by a different angle corresponding to the increased spacing in the direction of the applied tensile load. The residual stress is a function of the change in the two interplanar spacings relative to the unstressed condition.

By differentiation of Bragg's law, it is found that a difference in diffraction angles at the two angles is a measure of the change of the interplanar spacing. The equation for determining stress then is simply a constant times the shift in the diffraction angle.

The X-ray diffraction method of residual stress determination is non-destructive since only the X-ray beam touches the surface. The beam penetrates the material to less than 0.025 mm. Therefore only the surface stresses are measured. It is possible to obtain compressive stress readings below the surface by removing the top layer using a process that leaves the surface unaffected in terms of the compressive stress properties. This layer removal operation can be accomplished by an electro polishing process.

The X-ray diffraction method can now be used to map the stress profiles throughout entire surfaces. This provides accurate values for the residual compressive stress induced by shot peening or the resultant values for stress where there is residual stress combined with an applied load. It can also be used at any time during the life of a component to determine if relaxation of the compressive stress layer is occurring due to excessive operating temperatures or cyclic loads [26] [30].

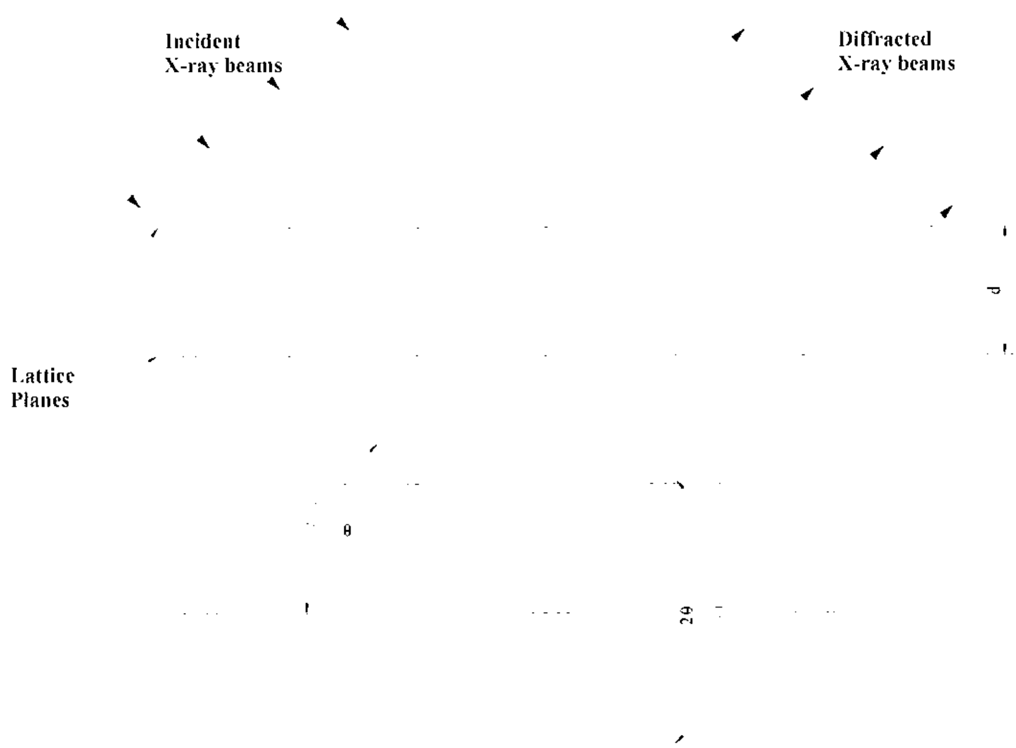


Figure 15. X-ray beam diffraction in accordance with Bragg's Law. [22]

Residual stress mapping, using X-ray diffraction techniques, can also be used to validate finite element analysis of critical local stress locations that are subjected to plastic strain and are likely to fail by fatigue. In many cases the application of shot peening to the critical areas may be beneficial.

3.2 Hole Drilling Method

The introduction of a small hole into a part containing residual stress relaxes such stresses locally, causing a change in surface strains in the immediate area of the hole. The state of biaxial residual stresses at and just below the surface can be determined from measurements of the changes in strain in three radial directions as the hole is produced [22].

The hole drilling technique begins with the installation of a three-element rosette type strain gauge as shown in Figure 16. The centre of the rosette is located to coincide with the point of stress measurement.

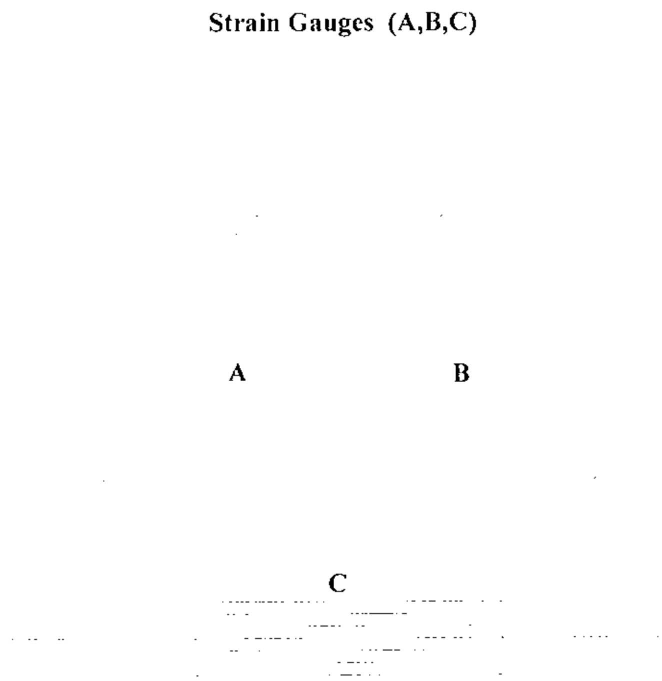


Figure 16. Strain Gauge Rosette. [22].

The strain gauge rosette is designed with three gauges located radially from the centre of the hole. The angles between the gauges are such that the magnitude and direction of the principal stresses may be obtained from the strain gauge readings.

A precision guide with optical alignment is then installed, with its centre located at the geometric centre of the rosette as shown in Figure 17. The optical alignment insert is then removed and replaced by a drilling guide. A small, flat-bottomed hole is then drilled or milled into the surface. The hole size may vary from 1.5mm to 3mm diameter with a depth equal to its diameter. The change in strain around the hole due to stress relaxation is measured by the rosette and read on a strain indicator. Stress is calculated using formulae that relate the measured strains, modulus of elasticity, Poisson's ratio and constants that are a function of the material and the hole geometry.

Attention must be given to the possibility of stresses being induced due to the drilling operation. This can be eliminated by the use of chemical milling or high speed drilling [22].

The hole drilling method requires that metal removal occurs therefore it is not a totally non-destructive method. The amount of metal removed is normally relatively small and the technique is often referred to as "semi destructive". The cost of the equipment for this technique is approximately 10% of the cost of an X-ray diffraction machine but it will only measure the stress at a single point for each operation. This would be a very difficult process to apply it to whole areas of a surface for the purpose of stress mapping.

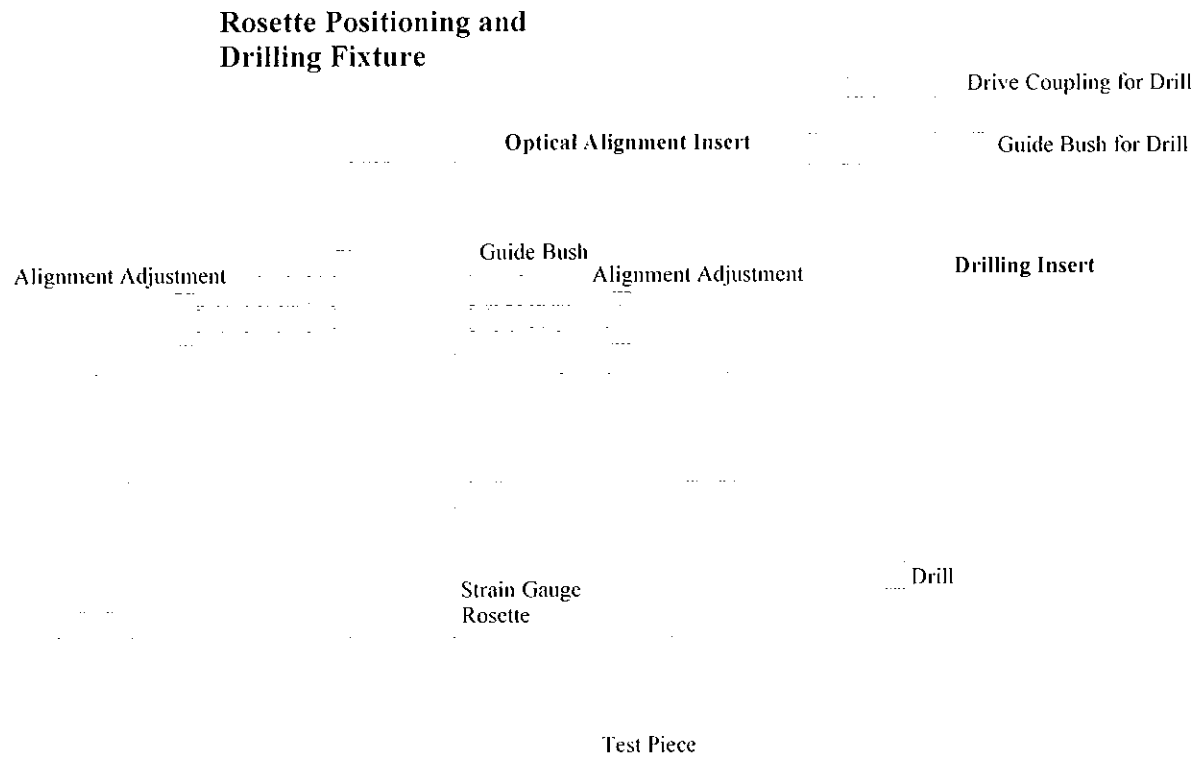


Figure 17. Fixture for Positioning Strain Gauge Rosette and Drilling Hole. [22]

3.3 Other Techniques for Determination of Stress

Various other techniques using ultrasound, magnetism and photoelastic coatings have been used for determination of residual compressive stress. Some of these methods have limits on the stress range that can be measured while other methods only give a qualitative result [22].

3.4 Residual Stress in Bulk Materials and Components

Manufacturing processes have a significant effect on the properties of metal parts. These effects can be detrimental or beneficial depending on the nature of the stresses, which will be encountered when the part is in use. Processes that leave the surface in residual tension are detrimental with regard to the initiation and propagation of surface cracks [22] [27].

3.5 Processes Resulting in Tensile Stresses.

Grinding

Electro Plating

Welding

Electro-discharge machining

Electro-chemical machining

3.5.1 Grinding

Grinding induces residual tensile stress as a result of localised heat generated during the process. The locally heated metal attempts to expand and since it is weaker than the surrounding metal it yields in compression. When this metal cools it attempts to contract but is resisted by the surrounding metal resulting in residual tensile stress. Shot peening after grinding will reverse the residual stress from tensile to compressive [2].

3.5.2 Electro Plating

Parts, which are to be chrome or nickel plated, are often shot peened to offset the potential detrimental effects on the fatigue life of the part. If cyclic tensile stresses are encountered the hard surface may develop minute cracks and these can propagate into the base metal. A compressive stress layer on the base material under the plating, will prevent propagation of these cracks into the base metal [2]..

3.5.3 Welding

The residual tensile stress, which is present in welded parts is created by the interaction between the molten weld consumable and the adjacent parts of the component. The consumable is molten and in an expanded condition while the adjacent parts are solid and initially cool. As the applied consumable solidifies, it will attempt to contract but is prevented from doing so by its bond with the parent metal. The heat affected zone (HAZ) is therefore in a tensile condition and prone to fatigue cracking and premature failure. The weld condition can be greatly improved by the application of shot peening to induce a residual compressive stress, which will reduce or cancel the tensile stress at the surface [2]. The benefits of shot peening to welded components may be optimised by first applying a stress relieving, heat treatment process.

3.5.4 Electro - Discharge Machining

This process is commonly referred to as spark erosion and involves localised melting of the material. This results in a thin layer of recast metal remaining on the cut surface of the finished component. This layer can be more brittle than the parent metal and be subject to residual tensile forces similar to those encountered in welding. The use of shot peening on the cut surface can eliminate this tensile layer and replace it with a stronger compressive surface layer [2].

3.5.5 Electro – Chemical Machining

This process involves the controlled dissolution of metal by the application of an electric current in the presence of an electrolyte. The cut surface of the metal displays softer characteristics than the parent metal. The surface also shows a marked increase in imperfections due to the preferential attack of the process on the grain boundaries of the material.

The application of shot peening after ECM strengthens the surface by the production of a residual compressive stress layer and eliminates the imperfections by cold working of the surface [2].

The beneficial effects of shot peening, on the fatigue strength of components which have been produced by a process that results in detrimental residual tensile stress, is shown in Figure 18.

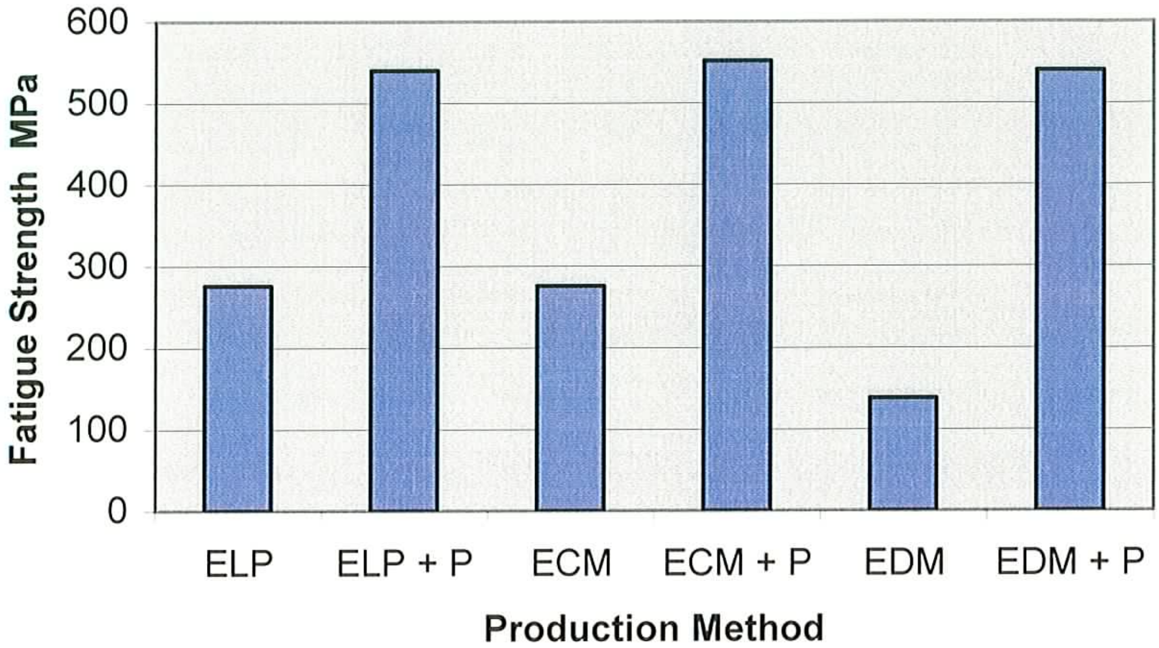


Figure18. Effect of Production Method on Fatigue Strength [2].

ELP.---------------- Electro Plating.
ELP + P. --------- Electro Plating followed by peening.
ECM.----- ---------Electro Chemical Machining
ECM + P. ---------Electro Chemical Machining followed by peening.
EDM.----- ---------Electro Discharge Machining
ECM + P. ---------Electro Discharge Machining followed by peening.

3.6 Processes Resulting in Compressive Stresses

Burnishing

Rolling

Polishing

Honing

Shot peening

The detrimental effects of the processes resulting in tensile stresses, listed in section 3.5 can be offset by the application of one of the processes listed in section 3.6 above. Most of these processes are limited to components or materials of regular shape or section. Shot peening, however, can be applied to practically any shape or section to achieve beneficial results.

3.7 Shot Peening Variables

The variables of the shot peening process are those factors, values or conditions that can be changed in order to achieve a specific result from the process. These variables will depend on the material being peened and the desired outcome of the process.

3.8 Peening Media.

This term refers to the material from which the shot is produced. Typical materials used as blast media include the following; Chilled cast iron, steel, aluminium oxide, ceramic, glass, corundum, plastic and walnut shells. Steel is the most commonly used shot for general shot peening, peen forming and peen straightening. Ceramic media is used for specialised applications such as the shot peening of hard metals and carbides. The media should be harder than the material to be peened [20]. It should be capable of resisting the force of impact so that no distortion or breakage of individual shot occurs. The media should not contain any contaminant that can be transferred to the material at the point of impact.

3.9 Media size.

The ideal shot is spherical in shape and the size refers to the diameter of the sphere. In any individual peening operation the shot size should be consistent. It is possible to obtain shot in sizes ranging from 10 micron to 10mm depending on the application of the peening process. As a general rule, small shot is for the production of compressive stress surface layers while large shot is used for peen forming operations. In micro-shot peening the shot sizes will typically be smaller than 500 microns (0.5mm) in diameter. The geometry of components, such as small radii, will influence the selection of the media size. As the size and mass of the shot are directly proportional to each other, the impact energy increases with the square of the diameter.

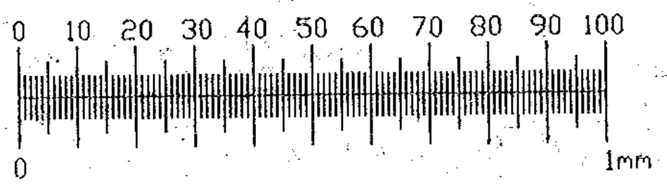
3.10 Media Condition.

The shape of the individual shot particles should be as close as possible to perfect spheres. These spheres may deteriorate in use as a result of the impact involved in the process. Depending on the nature of the shot material it may undergo plastic deformation or shatter during the process.

This damaged shot has to be separated from the undamaged shot before it is reused as it can have detrimental effects on the material or part being shot peened. Instead of producing a spherical shaped indentation, damaged shot may cause gouging or scoring of the surface, which may in time be the source of crack initiation.

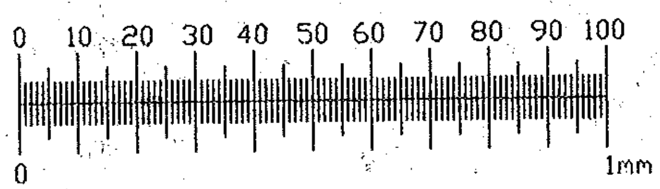
3.11 Coverage.

This term is used to indicate the completeness of the shot peening process, which is applied to the surface of a part. A coverage of 100% indicates that the original surface has been entirely obliterated by individual shot craters as shown in Figure 19. Coverage values over 100% may be obtained by shot peening the same area for a longer period of time than that necessary to obtain 100% coverage. Designers may specify coverage values between 100% and 400% on components. This is done to ensure the integrity of the compressive layer [37] [38] An example of incomplete coverage is shown in Figure 20.



100% Coverage

Figure 19. Complete Coverage (100%)



50% Coverage

Figure 20. Incomplete Coverage (50%).

Coverage is defined as the complete denting or obliteration of the original surface as determined by visual inspection using a 10X magnifying glass.

Coverage can be determined with better accuracy by the use of a peenscan process [2]. This requires the entire surface area of the part to be covered with a fluorescent dye, which is painted or sprayed onto the surface as a liquid and allowed to dry. When the dye is dried it forms an elastic tracer film on the surface. Shot striking the elastic tracer film breaks away the film only in the area of impact. Tracer remaining on the part will indicate areas where no impact has occurred, thereby indicating incomplete coverage.

3.12 Intensity.

This is a measure of the kinetic energy delivered by a stream of peening media for a given set of process parameters [20]. The kinetic energy of an individual shot is $0.5Mv^2$, where M is the mass of an individual shot and v is the velocity of the shot at the instant of impact [4]. Intensity is mainly a function of media velocity and individual media mass but media hardness and the angle of delivery of the media onto the surface of the material also have an influence on this variable [35] [36] . Media condition also has an influence on peening intensity as broken shot has lesser mass and therefore lower kinetic energy. The use of this type of shot will result in lower intensity of the media stream and possible damage to the material surface by the jagged edged particles.

As this variable, intensity, has several sub variables some of which are difficult to measure, a standard test for intensity, was developed by J.O.Almen. This involves the use of Almen strips that are subjected to the peening operation on one side only.

Standard Almen strips of different thickness are available for testing shot peening intensity [20]. Three strips are available and these are designated N, A and C. The strip thickness for these designations are as follows;

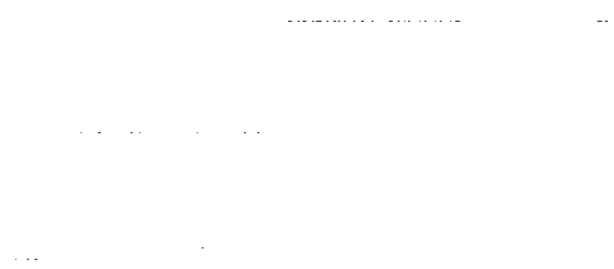
N = 0.8mm, A = 1.3mm, C = 2.4mm.

The material used in the strips is a heat treatable alloy steel SAE 1070 which is hardened to Rockwell C 44-50. The strips are 75mm long and 19mm wide.

3.12.1 Evaluating Intensity

The intensity is determined by peening the strip on one side while it is restrained in a flat condition in an Almen strip holder by four retaining pan head screws [20]. After peening the screws are loosened and the strip is released. This allows it to adopt its equilibrium condition that will be in the form of a curve due to the compressive stress on the peened side. The strip will have a convex curve on the peened surface as shown in Figure21. The arc height at the centre of the strip it then measured using an Almen test gauge. The gauge is set to zero with the flat, unpeened, Almen strip supported on four spheres which are located accurately on a base plane. The centres of the spheres must be positioned on a common plane to avoid rocking of the strip. After peening, the curved strip is replaced on the four spheres, which ensure point contact at the supporting points. The arc height is then determined using a dial test indicator. When the arc height is plotted against peening time it is found that a saturation point is reached where very little further distortion occurs with an increase in peening time. The saturation point is determined when after increasing the peening time by a factor of 2 the arc height does not increase by more that 10%. There is a linear relationship between peening time and peening intensity up to a certain point. When this linear relationship ends, the saturation point is reached. An example of a saturation point of 0.23mm after a time of four seconds is shown in Figure 22. A typical value for this point would be given as follows; 0.23mm A. This indicates an arc height of 0.23mm using an "A" type Almen strip. The conditions necessary to produce this saturation are carefully noted and reproduced in subsequent processes to obtain optimum or specified results on shot peened components. In order to verify intensity values on actual components it is possible to locate an Almen strip adjacent to the part, which is to be processed. The part and Almen strip are then peened together and the arc height of the strip determined after the process is complete. On complex parts it is usual to position several Almen strips at strategic points adjacent to the part to ensure that the correct intensity is achieved at these points.

The useable range of an Almen strip is from 0.10mm – 0.60mm arc height. A thicker strip is used if the arc height approaches the upper value limit of the strip being used. The intensity values of respective Almen strips have the following approximate relationships: N = 0.33A, C = 3A, C = 9N.



Unpeened Almen Strip

Peened Almen Strip

Figure 21. Almen Strips.

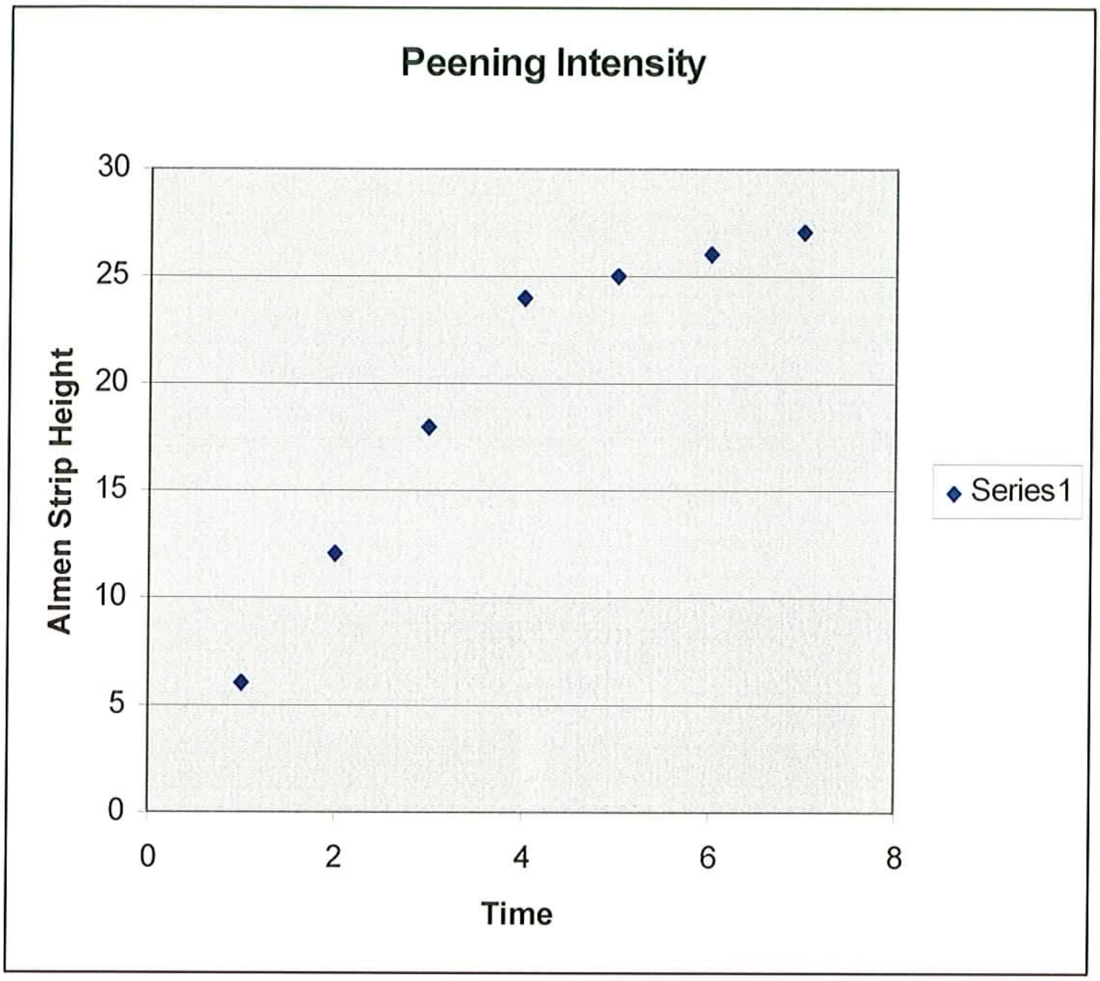


Figure 22. Peening Intensity. [2]

3.12.2 Intensity Specification [39]

The specification for shot peening on components is given by the following:

1. Almen strip type.
2. Arc height in millimetres.
3. Size of shot.
4. Shot material.
5. % coverage.
6. Permissible areas of overspray.
7. Surfaces to be masked.
8. The industrial standard being applied.(Appendix 2)

Chapter 4
Prototype Design.

4.0 Prototype Design.

In order to carry out detailed experimentation on the shot peening process it was necessary to build a test machine which had the capablity of varying all of the process parameters of shot peening. The process also required accurate control and good repeatability to enable reliable results to be obtained. The machine incorporated a shot storage and delivery system together with a shot distribution system

An Almen strip holder and an Almen gauge were also required to calibrate the machine and to monitor the intensity of specific operations on components or tools. These two accessories were manufactured to the dimensions shown in Figure 23. and 24. that conform to ISO 12686: 1999(E) [28].

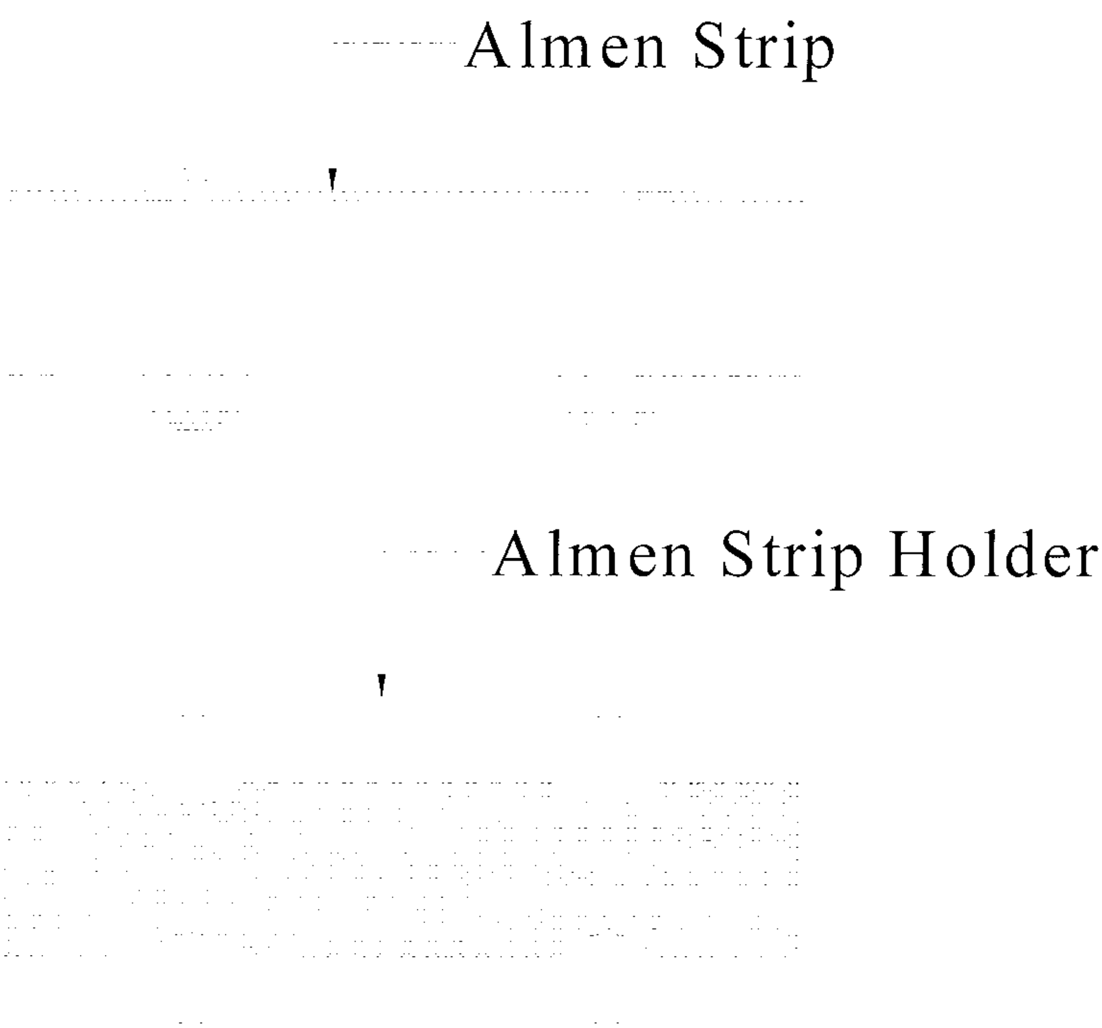


Figure 23. Almen Strip Holder [28].

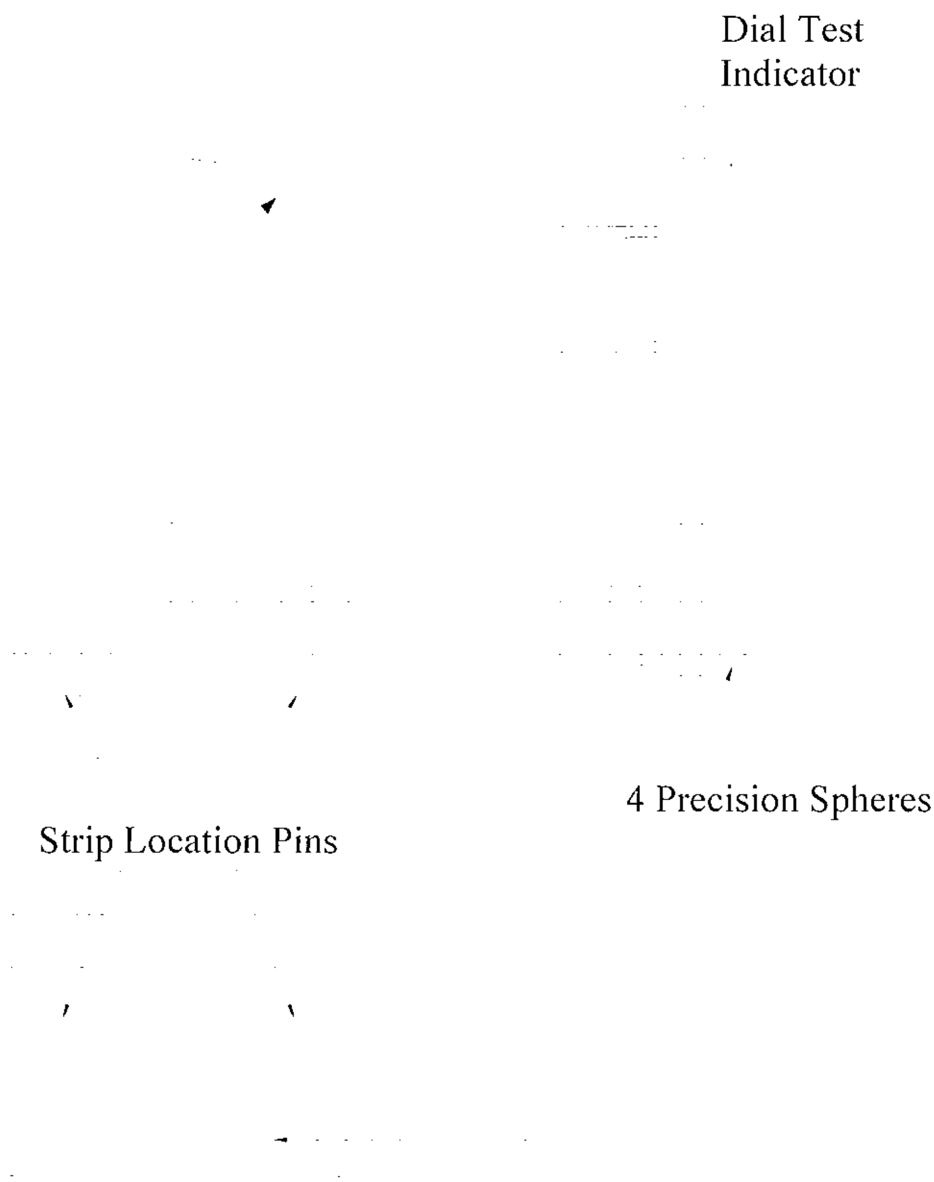


Figure 24. Almen Gauge [28].

4.1 Design and Manufacture of Micro Peening Process

The machine required the capability of projecting the peening media onto the surface of the test piece or component at a high velocity.

The velocity of the media stream needed to be adjustable.

The angle of impact of the media with the surface needed to be adjustable.

Experimentation with a wide range of media sizes had to be possible. The coverage required to be controlled and monitored.

The intensity needed to be adjustable and provision made for testing of this variable.

The peening process needed tot be applied uniformly over the test area, which had to be at least equal in area to that of an Almen strip.

The used shot needed to be saved and recycled.

The blasting area of the machine needed to be easily accessible for loading test pieces but totally sealed during operation.

The entire design required that all power and control systems were safe to use by qualified operators and inadvertent loss of power did not result in unsafe conditions arising.

4.2 Shot Delivery System

The delivery method of the shot onto the surface to be peened was by the use of a stream of compressed air. This method was considered more suitable for the nature of this project as other methods of delivering the shot such as centrifugal force (wheelapeening) or wet blast methods were considered more suitable for mass production operations [8].

The selected method involved the use of a nozzle, which was connected to a compressed air supply that incorporated a shot injection system as shown in Figure 25. Compressed air was supplied via the air filter and air inlet valve to the media reservoir as shown in Figure 26. The media, which is contained in the reservoir, is fluidised by the air passing through it. The air escapes from the reservoir via the rigid stand pipe and flexible hose to the nozzle. This air stream carries the peening media to the nozzle. The media enters the air stream through a small orifice in the wall of the rigid stand pipe, close to the bottom of the reservoir. Supply air pressure, the internal bore of the stand pipe and the diameter of the orifice determine the shot flow rate. The air pressure is varied by means of the regulator. A series of standpipes with different bore diameters ranging in size from 5mm to 10mm are interchangeable to vary the shot flow rate. These standpipes are also made with a range of orifice sizes from 0.5mm to 3mm diameter.

Figure 25. Shot Delivery Unit.

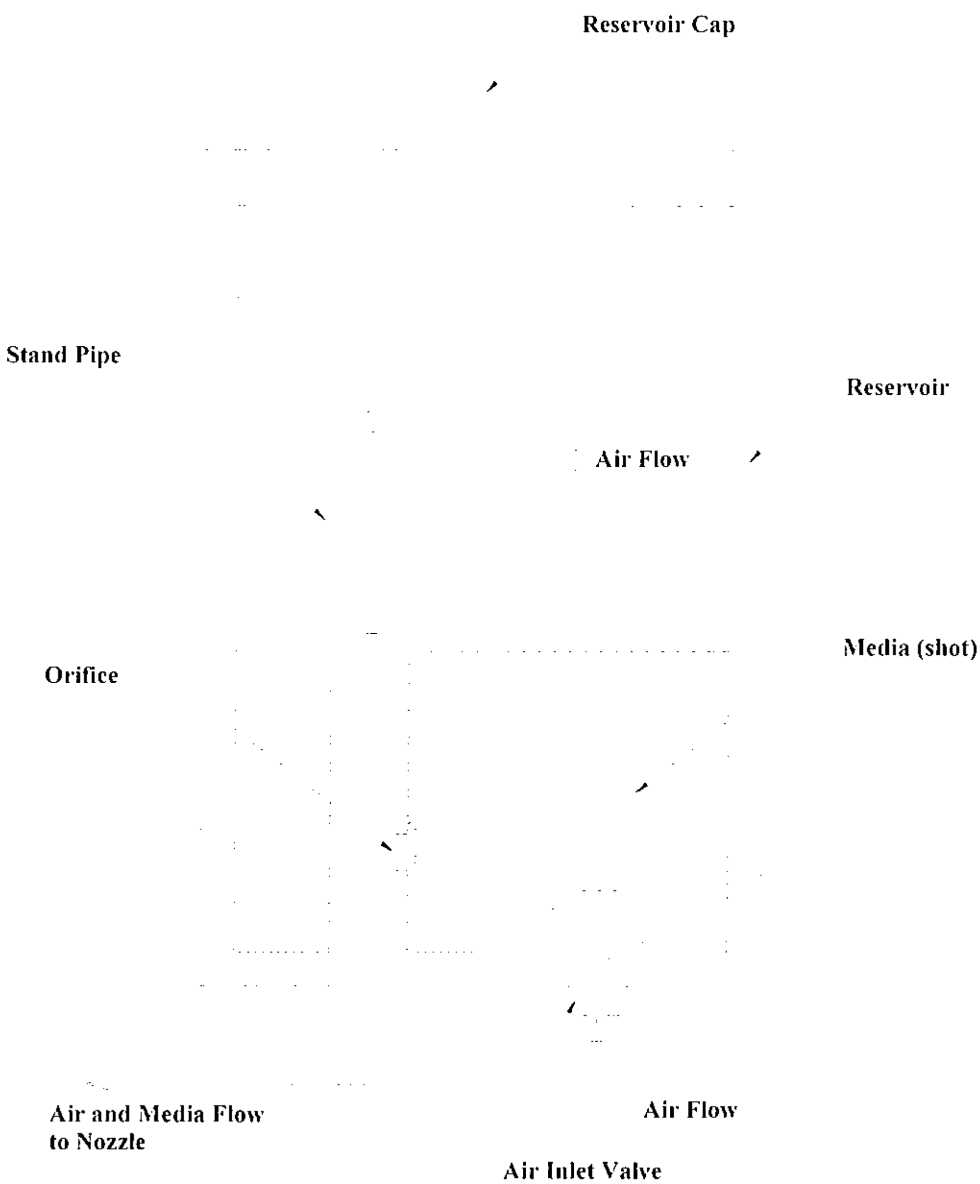


Figure 26. Shot Reservoir.

4.3 Shot Distribution System

The stream of projectiles are directed onto the material surface through a ceramic nozzle and are distributed over the material surface by the co-axial movement of the nozzle in the X and Y directions as shown in Figure 27.

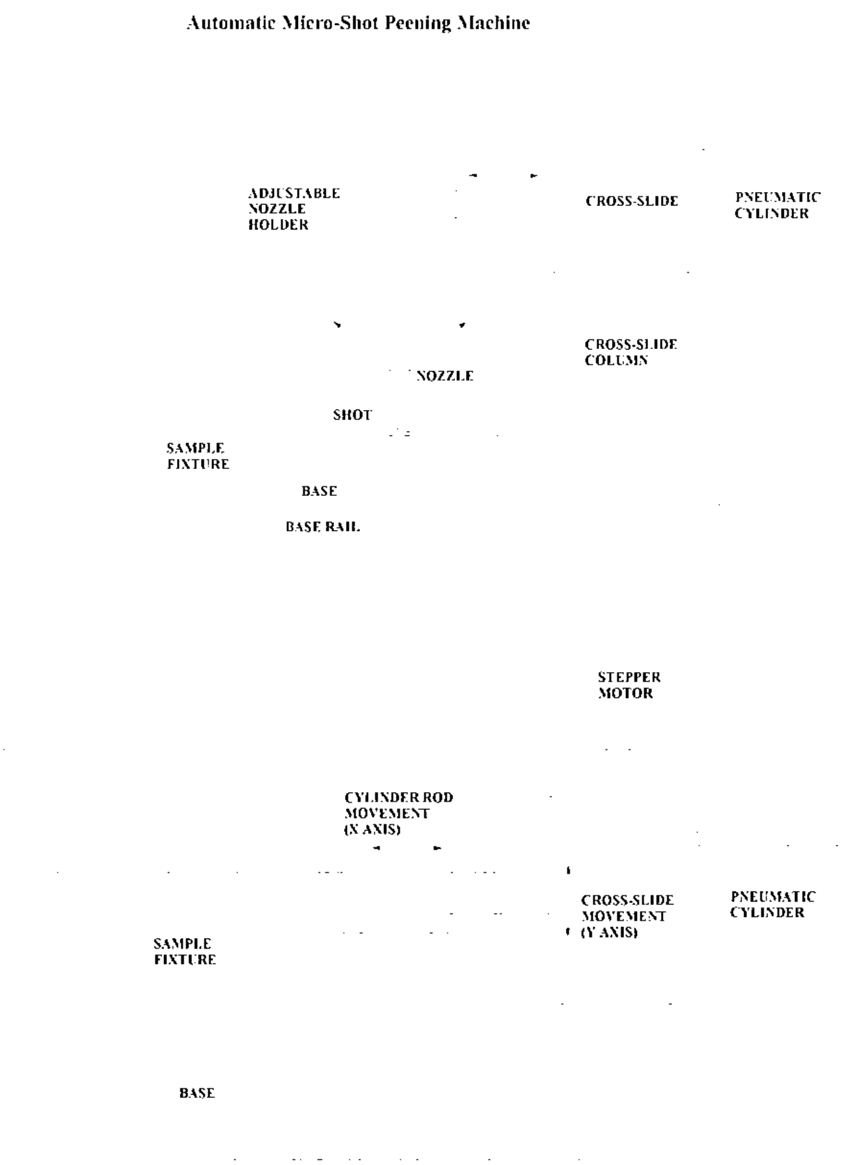


Figure 27. Shot Distribution Unit.

The nozzle angle is adjustable to vary the angle of impact of the projectiles with the surface. This was achieved by mounting the nozzle in an adjustable holder, which is graduated in degrees and is capable of limited rotation in an axis at 90° to the nozzle axis. A wide variation of this angle is not necessary as low angles of impact do not produce high residual compressive surface stresses [2] [20] As the velocity of the air stream is a function of the nozzle bore size, the nozzle discharge coefficient and the air pressure, this variable is controlled, by varying the air pressure and using a standard sized nozzle.

The nozzle bore was of sufficient diameter to allow for the use of a wide range of media size. Initially it was proposed to use micro-shot in the range of 150 micron to 300 micron diameter with a nozzle diameter of 2mm.The nozzle delivers a stream of projectiles onto the material surface. The width of this stream is dependent on the bore diameter of the nozzle and the distance of its outlet from the material surface. This distance determines the width of the media stream at the point of impact. The value for this width is given by the equation (4.1)

$$W = D/8 + d \qquad (4.1)$$

where D is distance from nozzle outlet to work surface and d is nozzle diameter.

Nozzles of different diameter are interchangeable and the distance from the nozzle outlet to the material surface is adjustable.

If the nozzle is moved in a straight line over the surface it will cause a strip of the surface to be shot peened. The area of this strip is equal to the stream width multiplied by the length of axial movement of the nozzle. In order to cover a test area on a material sample, the nozzle must be moved axially (x axis) for the required length and then moved laterally (y axis) by a suitable increment. This process is repeated until the test area is covered. The speed of the axial stroke and the amount of lateral increment is controlled and varied to ensure that the desired percentage coverage is achieved for any given set of conditions, (shot size, shot velocity, shot delivery rate, etc.). These values were determined during calibration of the machine. The distance from the nozzle to the test surface was adjustable to control the width of the projectile stream. Typically this distance was between 40mm and 100mm.

The axial stroke wase provided by a double acting, pneumatic cylinder with variable speed control in both directions as this is the most efficient method of obtaining linear motion and also allows independent control of the linear speed in both directions . A five port, two position directional control valve which is solenoid operated was used to control the cylinder movement. The use of a special hexagonal design of the piston and cylinder prevents rotation of the cylinder rod. This was essential for the correct positioning of the nozzle, which was mounted on a fixture at the end of the rod. The lateral, incremental movement was achieved by the use of a stepper motor and suitable leadscrew. This allowed the lateral increment to be varied over a wide range so that optimum coverage and intensity values could be achieved with a high degree of repeatability. The cylinder and nozzle assembly were mounted on the carriage of a linear slide unit with the stepper motor located on a fixture, which was secured to the bed of the linear slide unit. The position of this fixture on the bed was designed to be adjustable to allow for shot peening of test pieces with different geometries and dimensions. The entire assembly was mounted on a flat base. The base was fitted with two rails to provide a mounting surface for the machine and facilitate recovery of the shot.

A Programmable Logic Controller (PLC) was used to control the entire operation of the process. The PLC was connected to a dedicated stepper motor drive control unit. This facilitated the use of a wide range of stepper motor inputs, which assisted in the experimentation with coverage and intensity values. The solenoid valves were also controlled by the PLC. Part of the PLC program was written to control the Y axis incremental movements of the nozzle. The minimum increment was 0.1mm and the maximum increment was 75mm. This was achieved by varying the number of pulses transmitted to the stepper motor through the PLC. All electrical signals did not exceed 24 volts to meet the requirements of electrical safety. All moving parts were protected by fixed guards to minimise the risk of injury to operating personnel. These guards also protected the parts against the erosive effects of the shot media. The slide movements were fitted with automatic limit switches to protect the machine elements from damage due to over travel of the slide.

4.4 Process Enclosure

The shot peening machine and all the ancillary equipment was accommodated in a cabinet with two compartments. The upper compartment contained the shot delivery unit and the shot distribution unit. This compartment was sealed during the peening operation. Provision was made for recovery of the reusable shot. The lower compartment contained all the control and service equipment.

<u>Control equipment included the following:</u>

Power sources 240V AC, 24V DC, 12V DC.

Pulse generator.

Motor control card.

Programmable logic controller.

<u>Service equipment included the following:</u>

Air supply

Air filter, regulator and dryer.

4.5 Selection of Media

The media material was determined by the application of the shot peening process. As it was proposed to carry out testing on cutting tools that have a high hardness value, the media was required to have a higher hardness value. Glass beads and ceramic shot both fulfilled this requirement. Ceramic shot was used in preference to glass bead as it has a number of advantages in many applications [29].

Ceramic shot gives better impact resistance with breakage ratios of 5% of that of glass bead when used on hard materials.

The media condition is acceptable even after recycling up to 60 times.

There is no contamination of the component material as ceramic shot is chemically inert.

It can be used to produce a wide range of Almen intensities.

The surface roughness on the component can be controlled by shot size.

4.5.1 Ceramic Shot Specification

The ceramic shot consists of the following [28].

Chemical composition: ZrO_2 67%, SiO_2 31%, Other 2%.

Density: 3.85kg/l.

Hardness: 60 Rockwell C.

Colour: White

Size range: 100micron – 1180 micron.

4.6 Manufacture of the Microshot Peening Machine

A number of components for this prototype machine such as the stepper motor and control card were purchased. Some items such as the pneumatic cylinder, directional control valve and the PLC were provided by DIT. All of the mechanical components were manufactured from bar, sheet and other suitable material. This entailed extensive machining, metal forming and other fabrication methods in order to produce the required components. The components were assembled and connected to form a self contained working machine which requires only two external supplies.

These are ;

(i) An electrical supply of 220v, AC.

(ii) A compressed air supply with pressure up to 10 bar.

4.7 Shot Delivery Unit

The nozzle, air inlet valve, air filter, pressure regulator and pressure gauge were purchased as standard pneumatic accessories. The main assembly cabinet was made by modifying an electrical switchgear box and fitting it with suitable brackets and openings to accommodate the components as shown in Figure 25. The media reservoir and reservoir cap were machined from a billet of nylon and drilled and tapped to suit the inlet valve and stand pipe as shown in Figure 26. A number of different stand pipes were turned from brass and stainless steel bar. These pipes had different bore sizes and different orifice bores.

All of the components were assembled in the main assembly box and connected together using 6mm air line.

4.8 Shot Distribution Unit

The shot distribution unit consists of an assembly of several parts. A general view of this unit is shown in Figure 27. The base plate and rails were made from aluminium and machined to the dimensions shown in Figure 28. The rails were drilled and tapped and secured to the base by means of cap screws.

The cross slide unit, shown in Figure 29, was purchased and its bed was secured to the right hand end of the base at 90 degrees to the rails. The carriage of the slide unit was modified to enable the cylinder fixture to be attached to its top surface. This fixture, which is shown in Figure 30, was machined from a block of aluminium and allows the pneumatic cylinder to be located in a precise position relative to the slide unit axis and the plane of the base. The cylinder, which is of a special hexagonal design and incorporates flow control valves, was purchased together with a suitable directional control valve. The directional control valve is solenoid operated to allow electrical control of its operation. The stepper motor with a control card was also purchased. This motor was fitted with a flange mount that allowed it to be secured to a fixture by two screws. The motor fixture, which is shown in Figure 31, was machined from a block of aluminium to provide accurate location of the motor with the axis of the slide unit bed. A leadscrew that connects the motor to the cylinder fixture is shown in Figure 32.

The adjustable nozzle holder is shown in Figure 33. This consists of a fixed part and a movable part and was turned from a brass bar. The two parts were assembled by means of a threaded shaft that allows rotation of the parts relative to each other. A small flat was milled on the fixed part and a radial hole was drilled and tapped to assemble with the end of the cylinder rod. The nozzle is located in a radial hole in the moveable part. The distance of the nozzle outlet from the surface to be peened is adjusted by sliding the nozzle sleeve through the radial hole in the nozzle holder

An angular scale was machined into the circumference of the moveable part and a datum point was machined into the fixed part. This provides accurate angular positioning of the nozzle relative to the plane of the work surface. . A nozzle sleeve was turned from a round bar and the nozzle retaining nut was turned from a hexagonal bar as shown in Figure 34 A limit switch extension arm was machined from a block of aluminium as shown in Figure 35. This provides location and support at the extreme positions of the cylinder movement for the two limit switch brackets that are shown in Figure 36. A leadscrew cover was turned from an aluminium bar as shown in Figure 37. This protects the precision leadscrew from the abrasive effects of the shot.

4.9 Process Enclosure

A process control cabinet was modified in order to provide a sealed shot peening process enclosure unit with two separate compartments. The upper compartment is accessible by means of a hinged, sloping lid into which was fitted a shatterproof, perspex viewing panel as shown in Figure 38. Details of the equipment in the upper compartment are shown in Figure 39.

The lower compartment is fitted with two shelves and is accessible by a sealed door as shown in Figure 40.

4.10 Assembly

The stepper motor and the solenoid valves were located in the upper compartment with the shot delivery unit and the shot distribution unit as shown in Figure 38.

All the other electrical components were located in the lower compartment. The parts for the shot distribution unit were assembled using suitable bolts, nuts and dowels. The nozzle was fitted to the nozzle holder by means of a threaded sleeve. The leadscrew cover was fitted to a boss on the stepper aand secured with a grub screw. The directional control valve (DCV) was mounted on the inside of the upper compartment.

This shot distribution unit and the shot delivery unit were positioned in the upper compartment and the nozzle was connected using a 6mm air line. The two 6mm air lines from the directional control valve to the cylinder were fitted. The air supply from the service unit (Filter, Regulator, Isolating Valve) to the DCV and the shot delivery unit was connected through a sealed gland in the floor of the upper compartment. The limit switch extension arm was fitted to the rod end of the cylinder and the two limit switches were located in the required positions. These switches, which are normally open, are operated by contact with the nozzle holder. All the electrical wiring was passed through a second sealed gland to the lower compartment. The electrical wiring was completed to the control equipment in the lower compartment as shown in Figure 40.

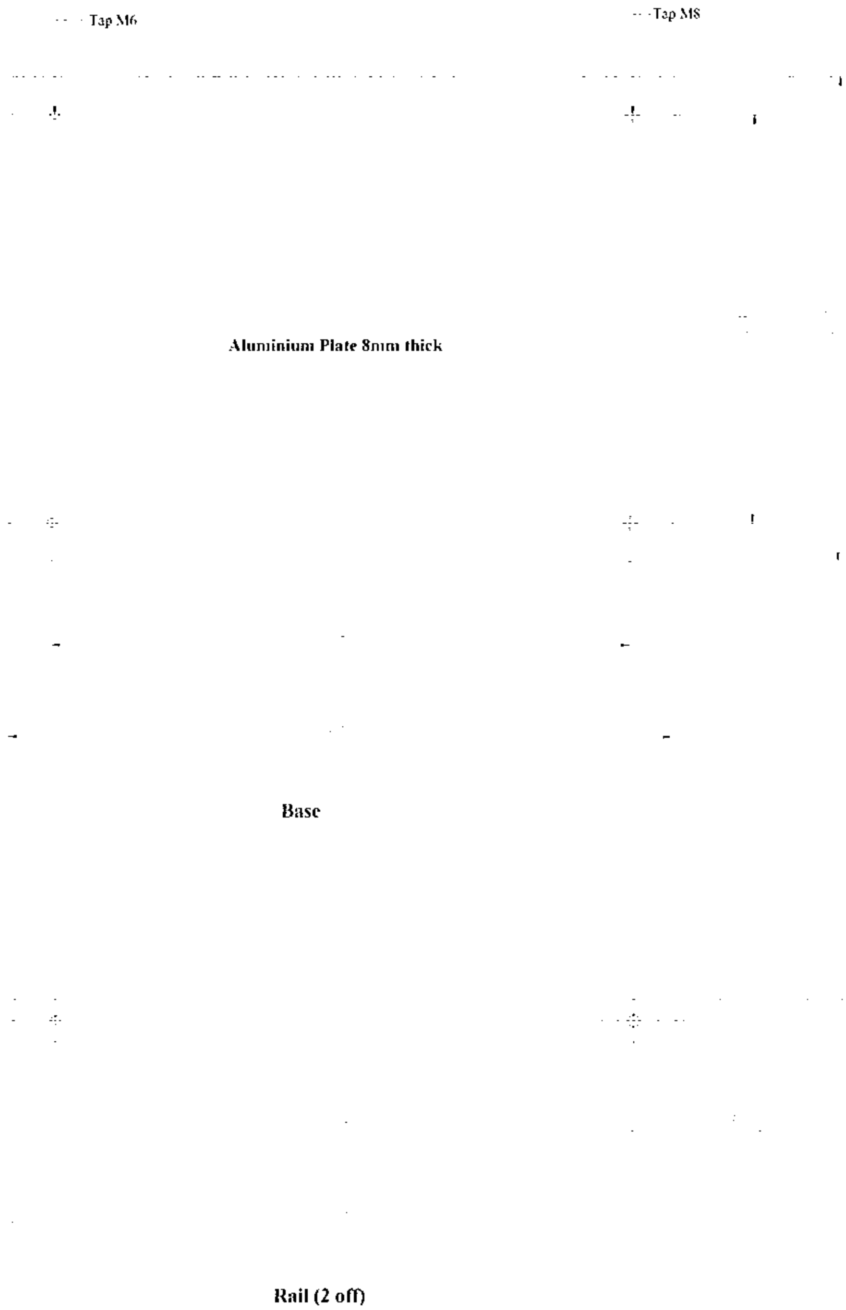


Figure 28. Base and Rails

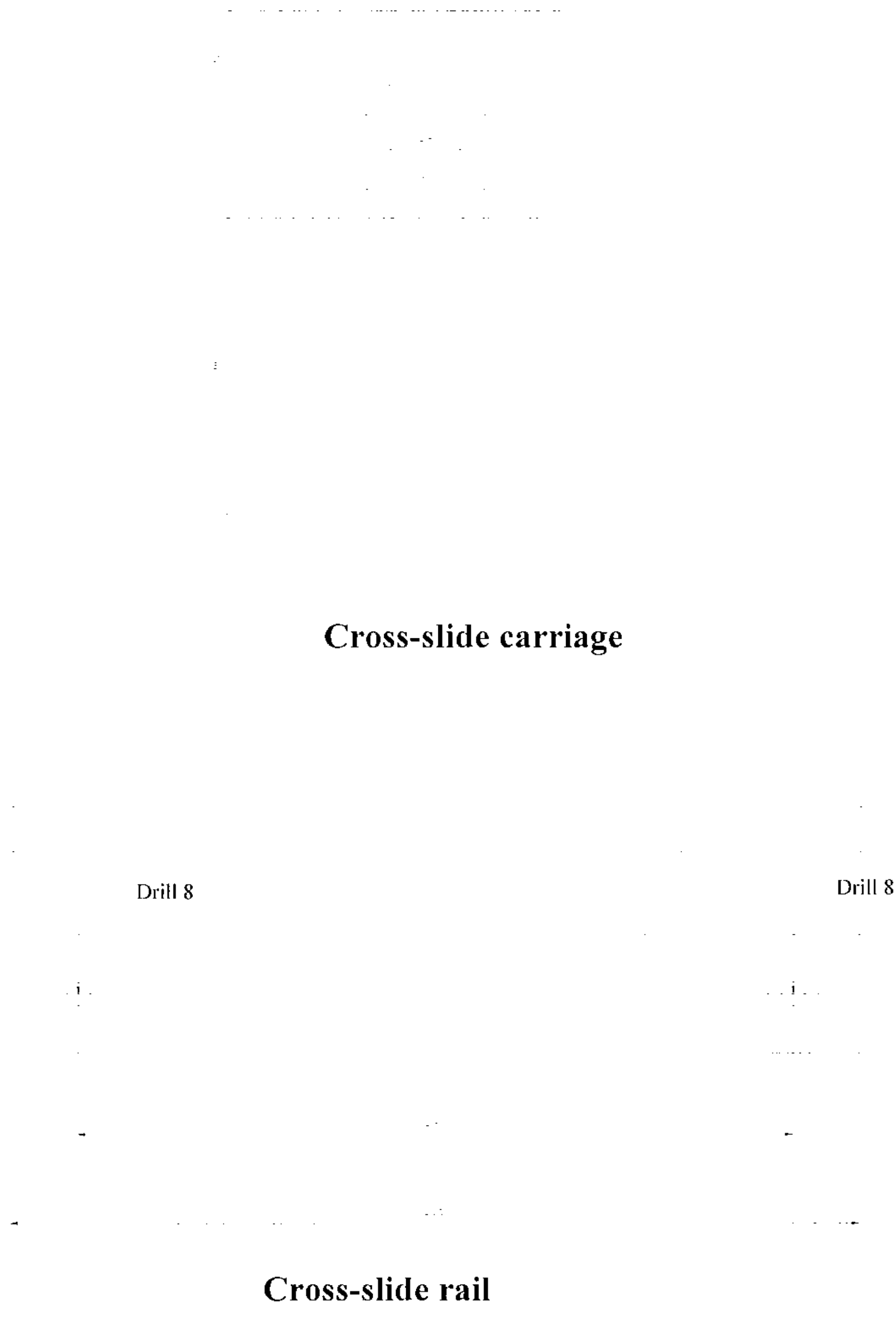


Figure 29. Cross Slide Assembly

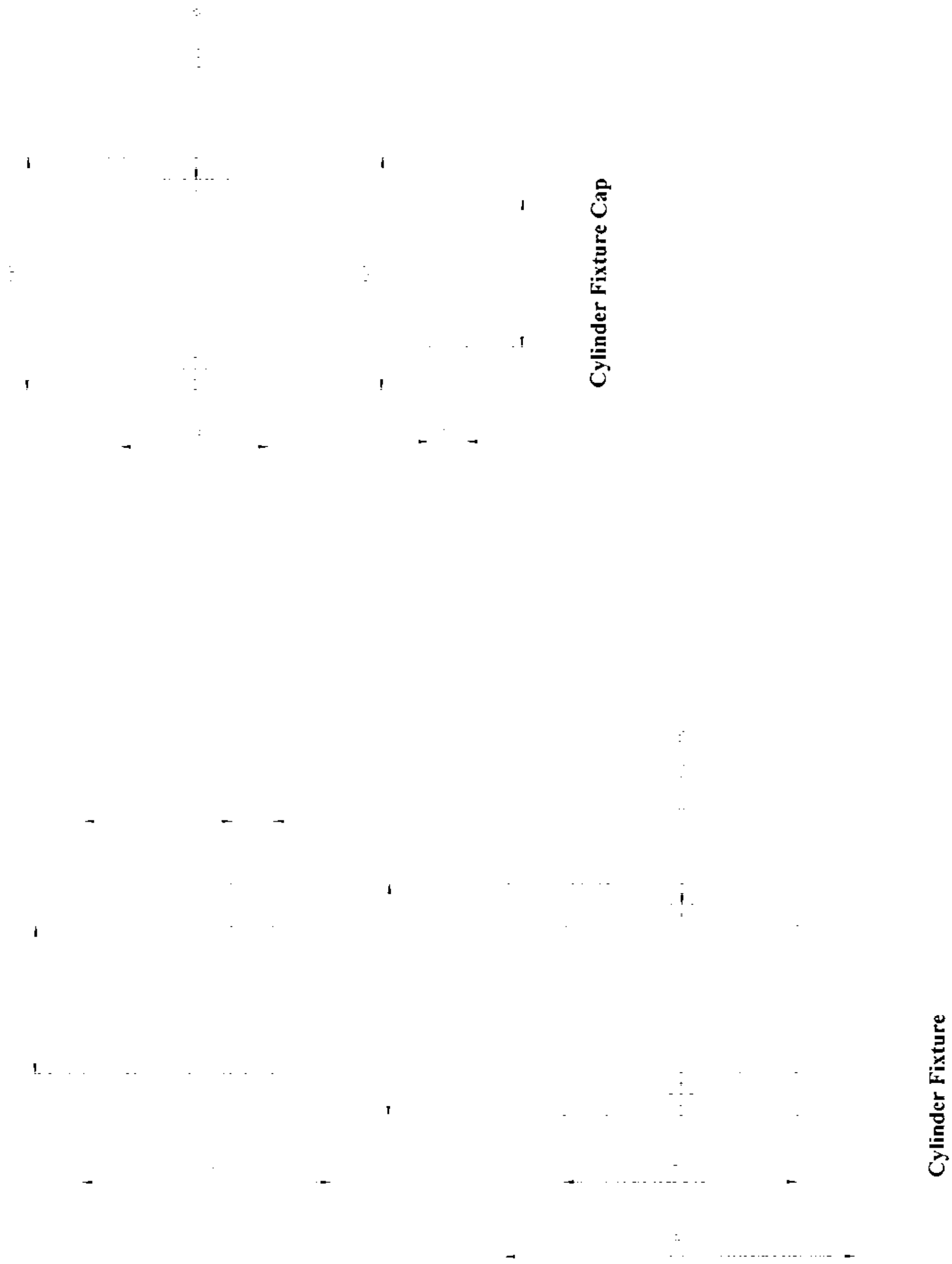
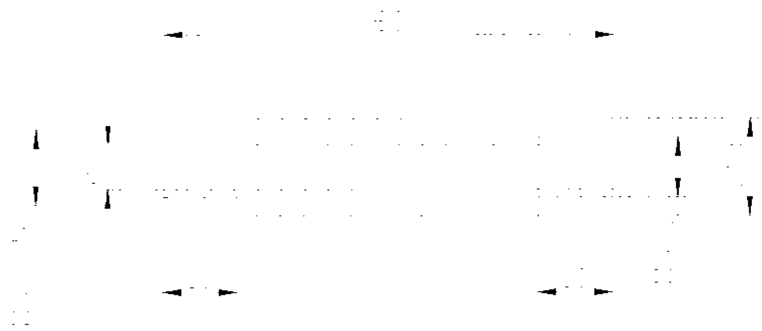


Figure 30. Cylinder Fixture and Cap

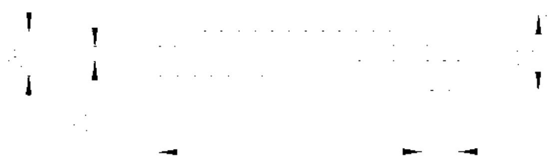
Figure 31. Stepper Motor Fixture

Figure 32. Leadscrew

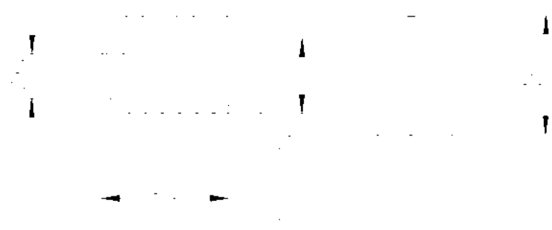
Figure 33. Nozzle Holder



Nozzle Sleeve



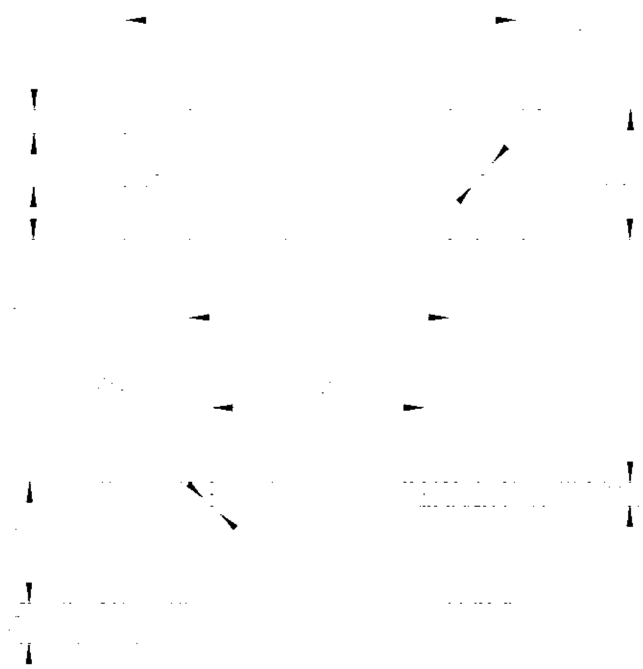
Nozzle



Retaining Nut

Figure 34. Nozzle Assembly.

Figure 35. Extension Arm for Limit Switches 1 and 2.



L.S. Bracket (2 Reqd.)

Figure 36. Brackets for Limit Switches 3and 4.

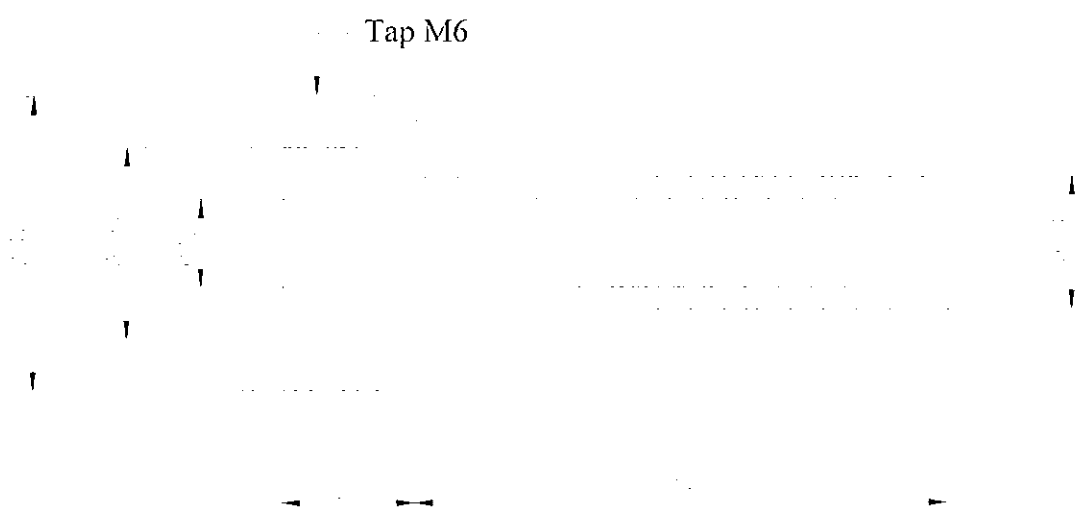


Figure 37. Leadscrew Cover.

Figure 38. Shot Peening Cabinet

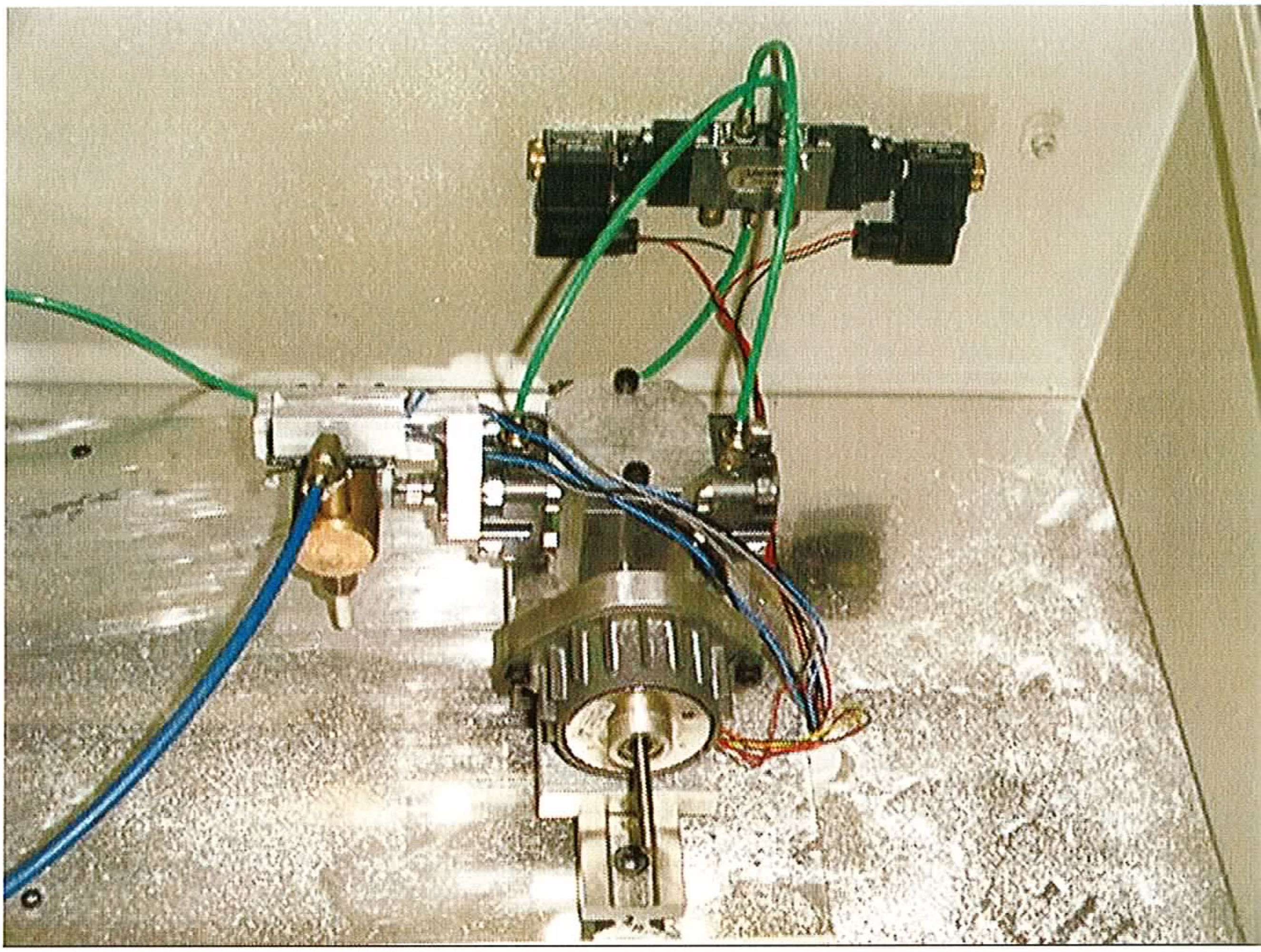


Figure 39. Shot Distribution Unit, Upper Compartment.

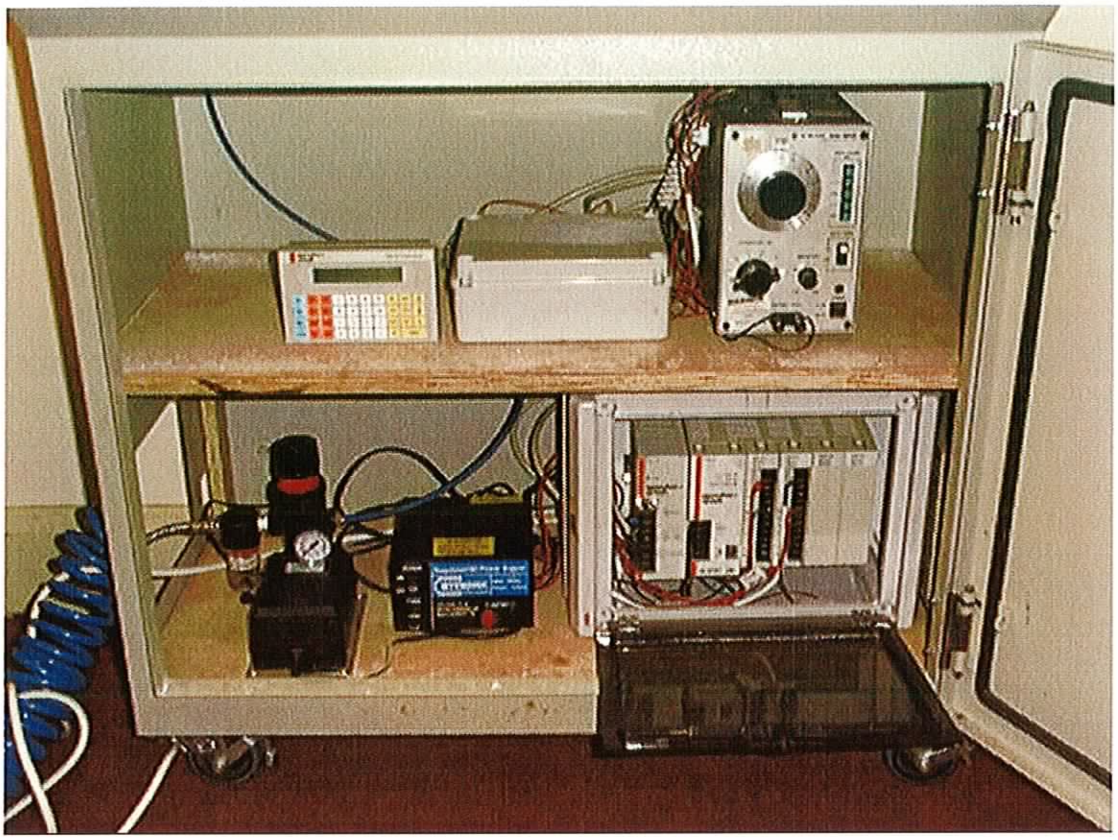


Figure 40. Electrical Control Components, Lower Compartment.

Details of the electrical components connections are shown in Figure 41. Details of the motor and control card wiring are shown in Figure 42 The circuit for the electro/pneumatic component connections are shown in Figure 43. Automatic control and reversal of direction of the axis movement is achieved by a PLC, limit switches and relays as shown in Figure 44.

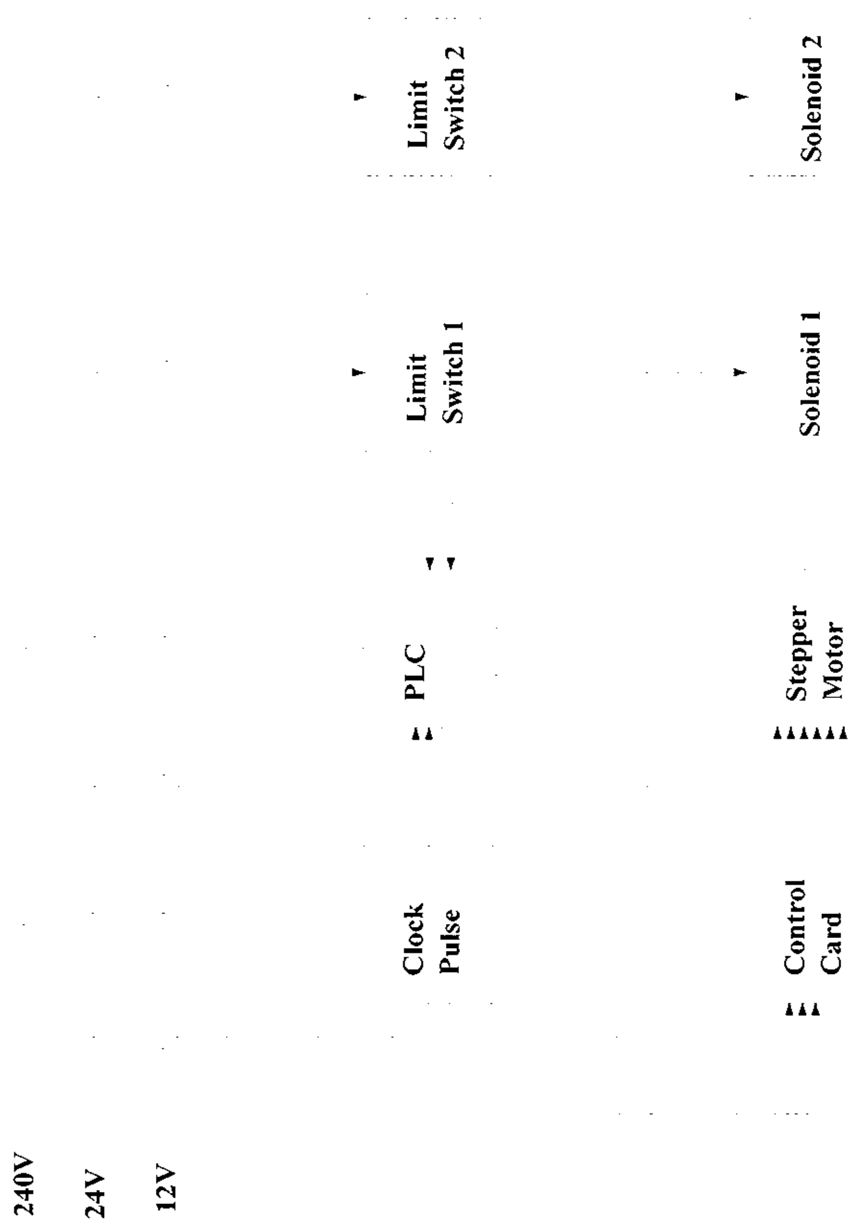
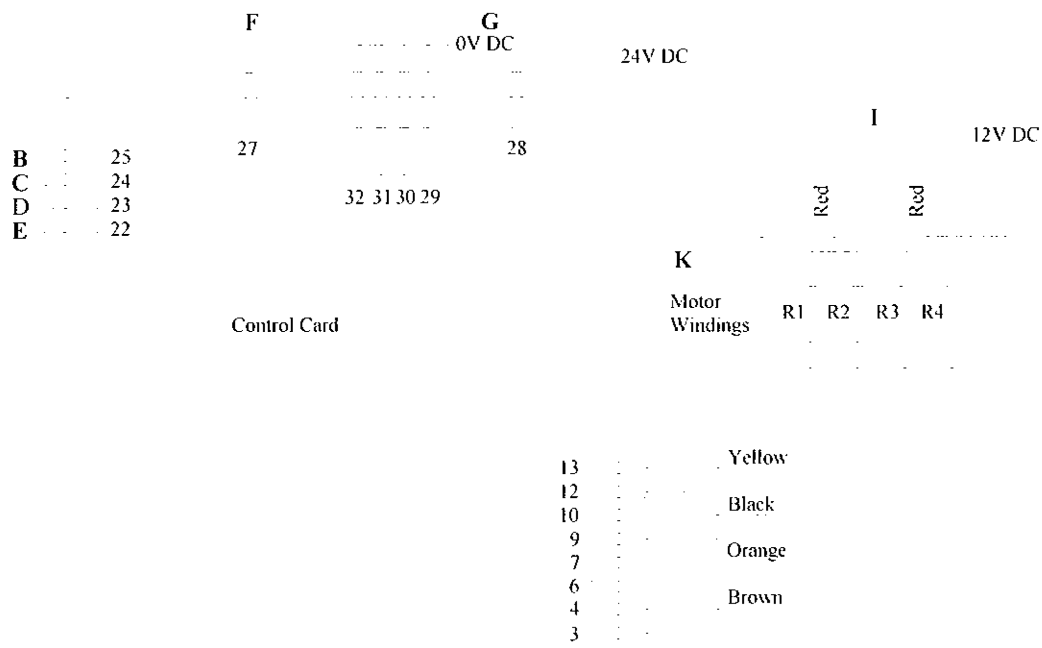


Figure 41. Electrical Circuit Block Diagram



Card Connections

B. Full / half step.
C. Clock.
D. Direction.
E. Preset.
F. Auxiliary output 12 V.
G. Board supply 24V.
I. Motor supply 12V.
K. Motor.

Figure 42. Control Card and Motor Connections

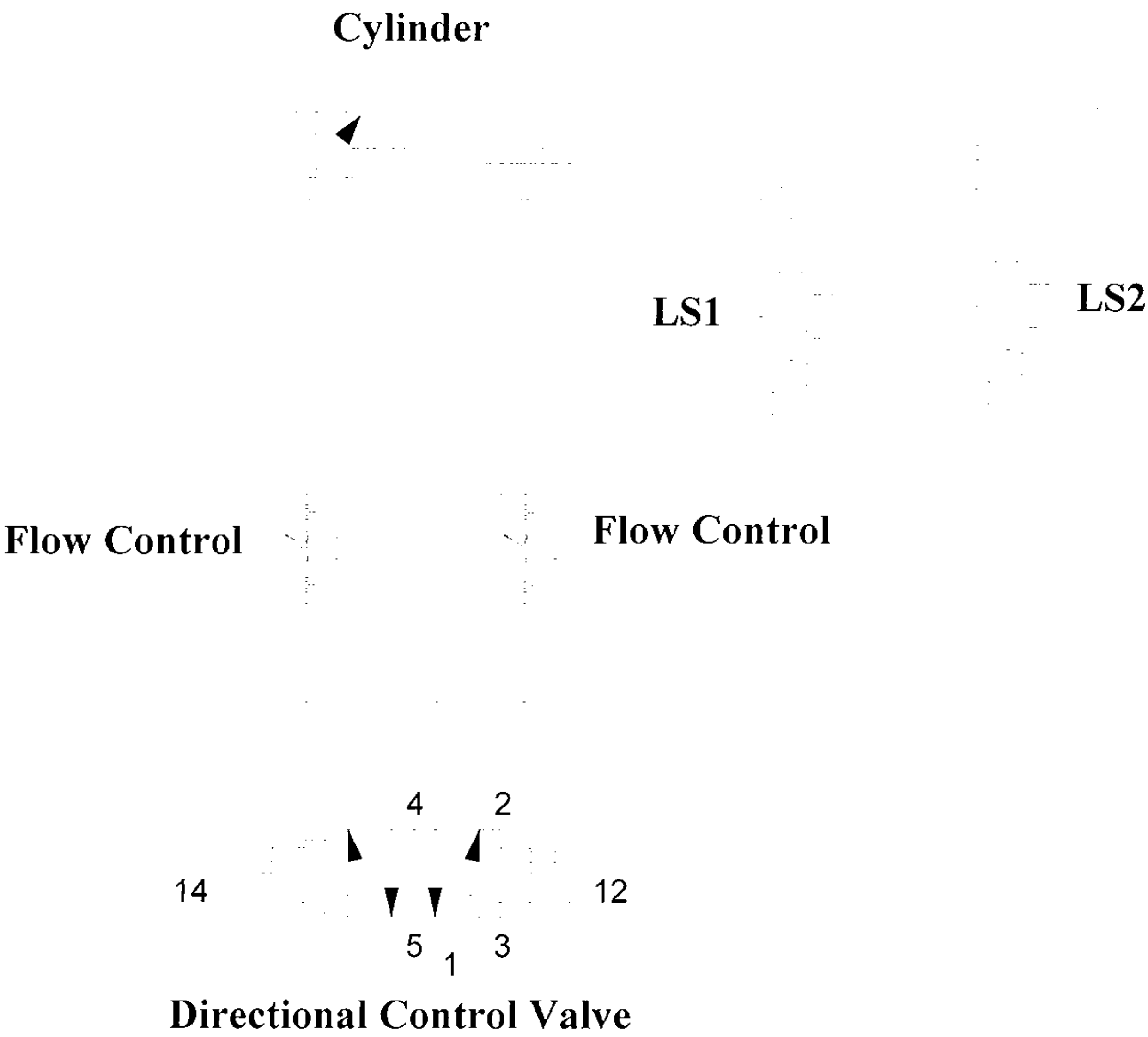


Figure 43. Electro/Pneumatic Circuit

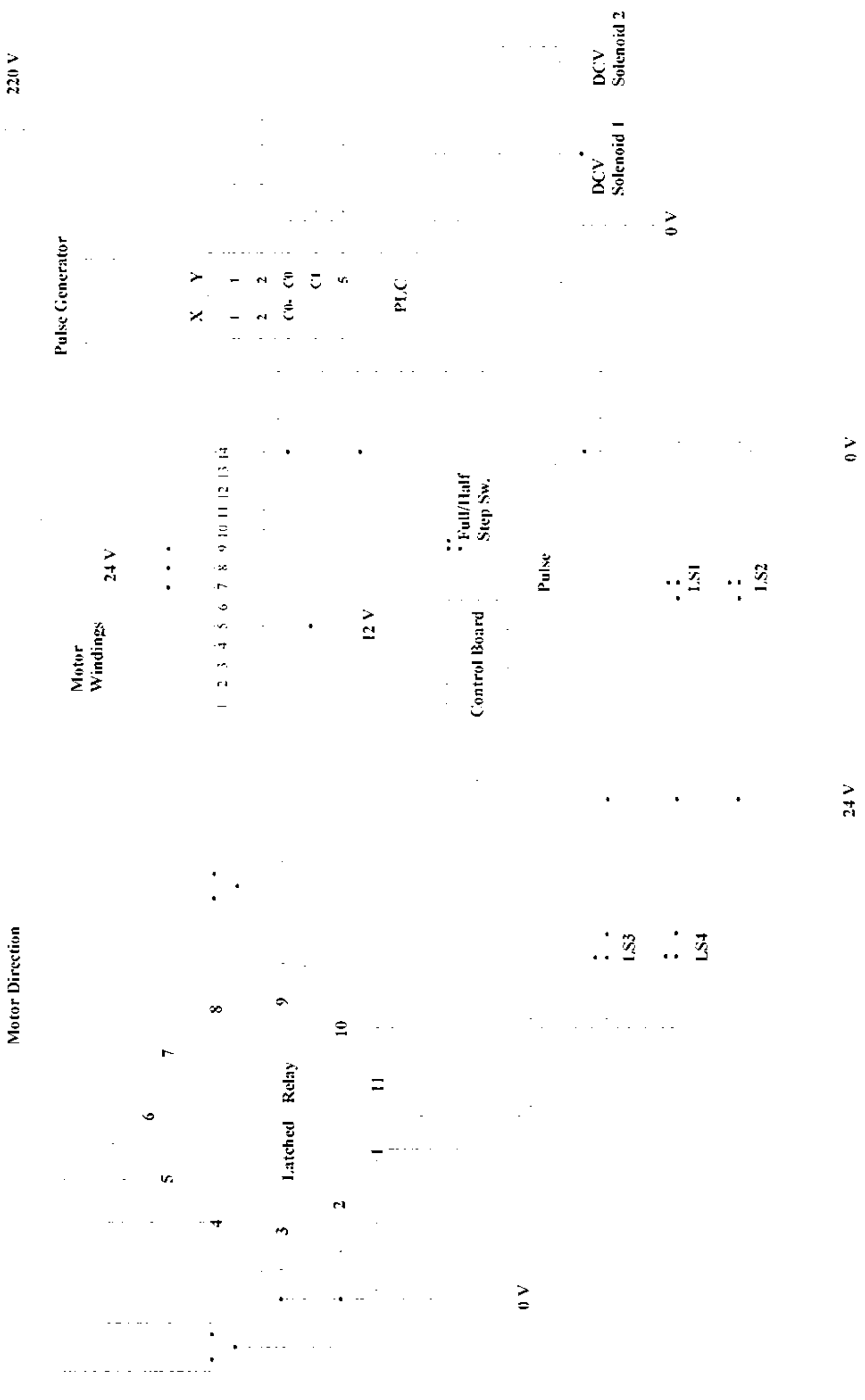


Figure 44. Wiring Diagram for Automatic Axis Control.

4.11 Calibration of Machine

Calibration of the machine was carried out by shot peening a series of Almen strips. The air pressure, the distance of the nozzle from the strip, the angle of impact and the type and size of shot used were all carefully noted.

4.12 Coverage.

The Almen strip was placed in the Almen strip holder and this assembly was placed on the table under the nozzle. When the air supply was turned on a shot stream was delivered from the nozzle outlet. This was directed onto an area just behind the strip. When the PLC programme was run the nozzle was moved forward in the X axis at a specific velocity. The stroke length was such that the travel of the nozzle exceeded the width of the strip. At the end of the stroke the nozzle was returned to its original position in the X axis, at this point the nozzle was moved by a suitable increment in the Y axis. The forward movement of the nozzle was then repeated. This cycle of operations was repeated until the entire area of the strip was peened. The strip was then removed and inspected visually for coverage. It was necessary to peen several strips for increasing periods of time in order to obtain 100% coverage. This was done experimentally by varying the velocity in the X axis or the incremental step over in the Y axis, this in effect varies the exposure time of the strip to the peening process.

4.13 Intensity.

When a strip with 100% coverage was obtained the arc height of this strip was measured using an Almen gauge which had been set to zero using a precision parallel strip of equal thickness to the Almen strip. The arc height was then plotted on a graph against the time taken to produce this arc height. This operation was repeated several times with new Almen strips that were exposed for increasing lengths of time to the peening process. The arc heights and peening times were plotted on the graph. From this graph the saturation point was established. This was determined by observation that when peening time was doubled the arc height did not increase by more than 10% [20].

A number of strips were then peened using the above conditions but varying the air pressure. By increasing the air pressure and hence the media velocity higher values of intensity were achieved. This was indicated by higher arc heights for the same exposure time, which agrees with published data on this topic [20].

The same procedure was repeated with a larger shot media and all other parameters remaining constant. The results showed higher intensity levels for the same exposure time. These initial results concur with well known data on intensity levels produced by higher mass shot [30].

Chapter 5

Testing of Shot Peened Materials and Components

5.0 Testing of Shot Peened Materials and Components.

Materials and tools were shot peened under controlled conditions and were then subjected to various tests to determine any changes or improvements.

5.1 Experimental Work on Twist Drills.

A number of 10mm diameter high speed steel twist drills were micro-shot peened using a shot peening machine. The machine uses an air stream to deliver the shot onto the surface to be peened. The air pressure is adjustable within the range of 1 to 10 bar. The shot distribution system consists of a ceramic nozzle mounted on a fixture at the end of a pneumatic cylinder. The fixture allows the position of the nozzle outlet relative to the peened surface to be adjusted and the angle of impact to be varied to angles other than 90°. The cylinder provides movement of the nozzle in the x axis and the linear speed of the cylinder is controlled in both directions by variable flow control valves. A precision cross-slide that is controlled by a leadscrew and stepper motor provides accurate incremental movement in the y axis. Adjustment of the air pressure, the cylinder linear speed and incremental step movement of the cross-slide provide conditions for precision peening in order to produce optimum conditions on surfaces of components. Ceramic shot was used for the peening operation. A series of Almen strips were peened at different air pressures and exposure times in order to establish known intensity values.
A special indexing fixture was used to hold the drill, position it correctly relative to the shot stream and rotate it to expose all relevant surfaces to the shot impact. The variable conditions of the peening operation are given in Table 2.

Variable	Value
Air pressure.	5bar
Nozzle Diameter.	2mm
Nozzle to surface dimension.	45mm
Angle of impact.	90°.
Cylinder speed.	1.2 m/sec
Increment in y axis.	0.04mm
Coverage.	100%
Intensity.	0.55A
Media Type.	Ceramic Shot
Ceramic Shot Specification.	
Chemical composition.	ZrO2 67%, SiO2 31%, Other 2%.
Density.	3.85 kg/l
Hardness.	60 Rockwell C
Colour.	White
Media size.	300 microns

Table 2. Operating Conditions of the Peening Process

Cutting tests were carried out on bright mild steel plate using high speed steel twist drills. Two sets of drills of diameter 10mm were used for the tests. One set of drills was micro-shot peened and the other set was used in its original condition. Images of the drill points were recorded, using a microscopic camera, before and after the cutting tests. The mild steel plates that were used as test pieces were 100mm x 100mm x 25mm thick. Each drill was used to produce 36 holes in a plate. The holes were peck drilled, with a peck distance of 2mm and complete withdrawal of the drill from the plate at the end of each peck. The drill diameter was 10mm, rotational speed 1000 R.P.M and feed rate of 50mm per minute. These parameters resulted in a cutting speed of 31.4 metres per minute and a feed per revolution of 0.05mm. A continuous flow of coolant was applied during the cutting cycle. The holes were centre drilled to a specific depth before the drilling operations. All the drilling operations were carried out on a three axis drilling machine with full computer numerical control in order to obtain constant cutting conditions for all of the tests.

On completion of the 36 holes in each plate the following tests and observations were made.

(i) Condition of drill, using images from microscopic camera.

(ii) Surface finish of hole using Talysurf.

(iii) Diameter of holes measured using CMM

Results

Condition of Drill

Figures 45 and 46 show the condition of the drill edges for peened and unpeened drills respectively before they have been used. The peened drill shows a slight rounding of the lip edge in comparison with the sharp edge of the unpeened drill. Figures 47 and 48 show the condition of the drill edges for peened and unpeened drills respectively after they have been used to peck drill 36 holes each. The peened drill, shown in Figure 47, remains relatively unchanged while the unpeened drill, shown in Figure 48, shows clear signs of lip damage.

Surface Finish of Hole.

The surface finish of all the holes was measured and recorded. The Ra. values for all holes produced by peened and unpeened drills are shown in Table 2. The comparative Ra. values for both sets of holes are shown in Figure 49. The graphs show clearly that the peened drill produced better surface finishes in practically all of the holes and as the drilling of the holes continued the difference in surface finish became more pronounced.

Diameter of Holes

The diameters for the 36 holes produced by the peened drill and the 36 holes produced by the unpeened drill are shown in Table 3. It is shown that the unpeened drill begins to drill oversize holes and this increase in size progresses with the number of holes drilled. This is due to unequal cutting forces on the drill causing it to deflect off centre. The peened drill also produced oversize holes but there was no increase in this error as the drilling operation continued. The comparative diameter values for both sets of holes are shown in Figure 50.

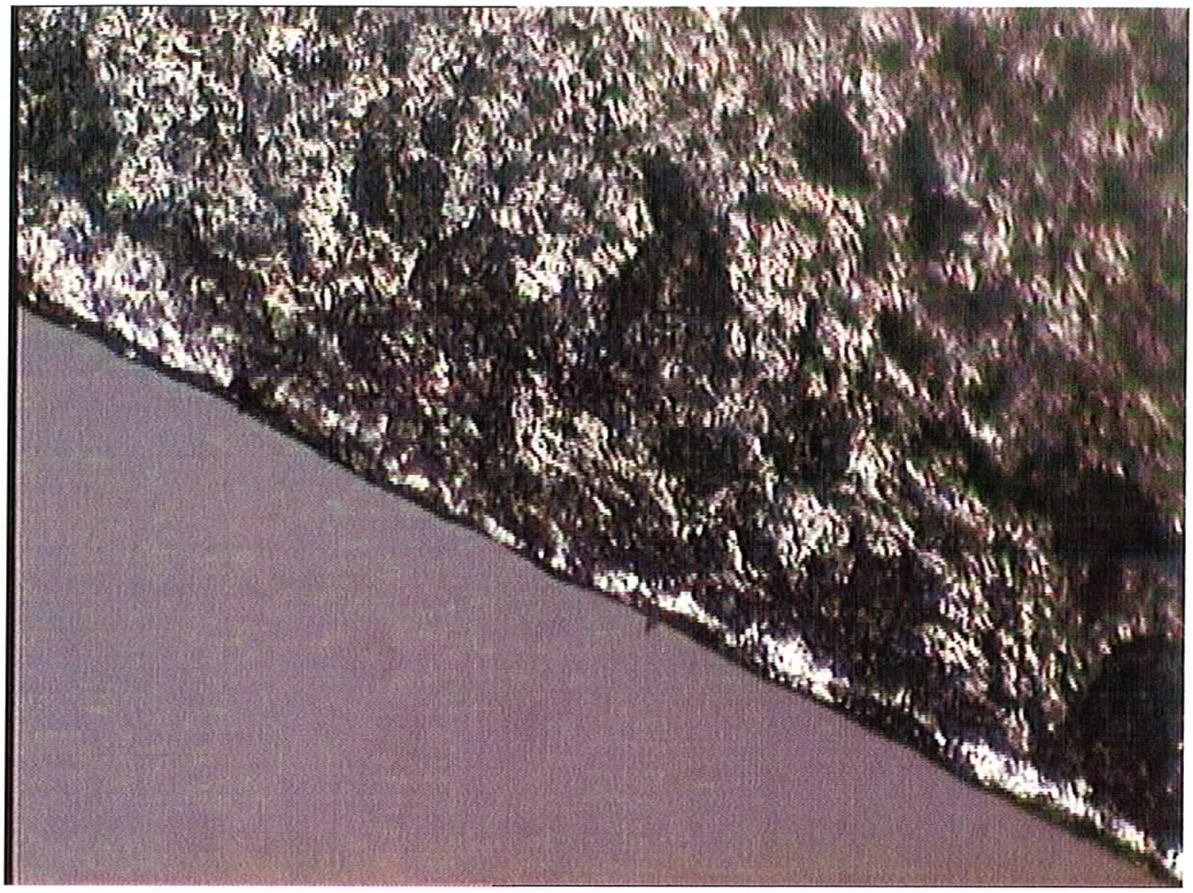


Figure 45. Lip of Peened Twist Drill Before Use.

(Magnification X 32)

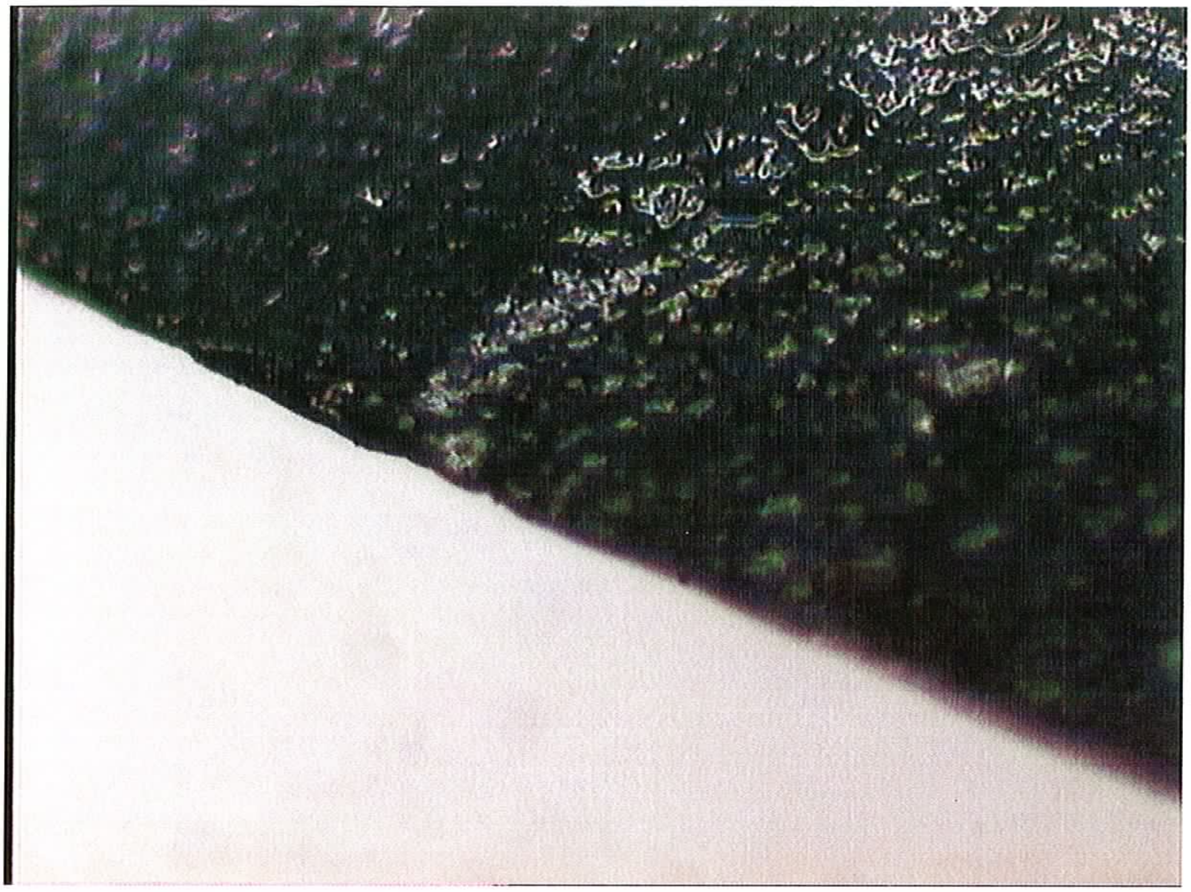


Figure 46. Lip of Unpeened Twist Drill Before Use.

(Magnification X 32)

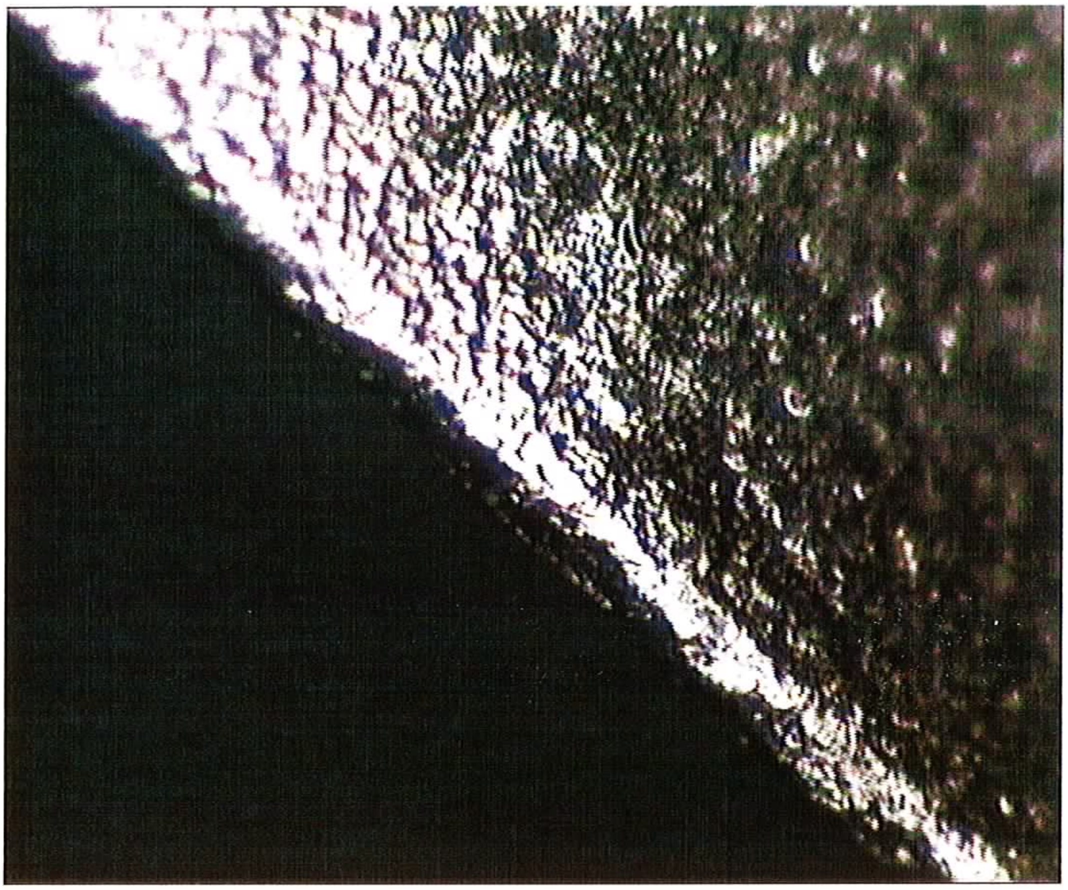


Figure 47. Lip of Peened Twist Drill After Use.

(Magnification X 32)

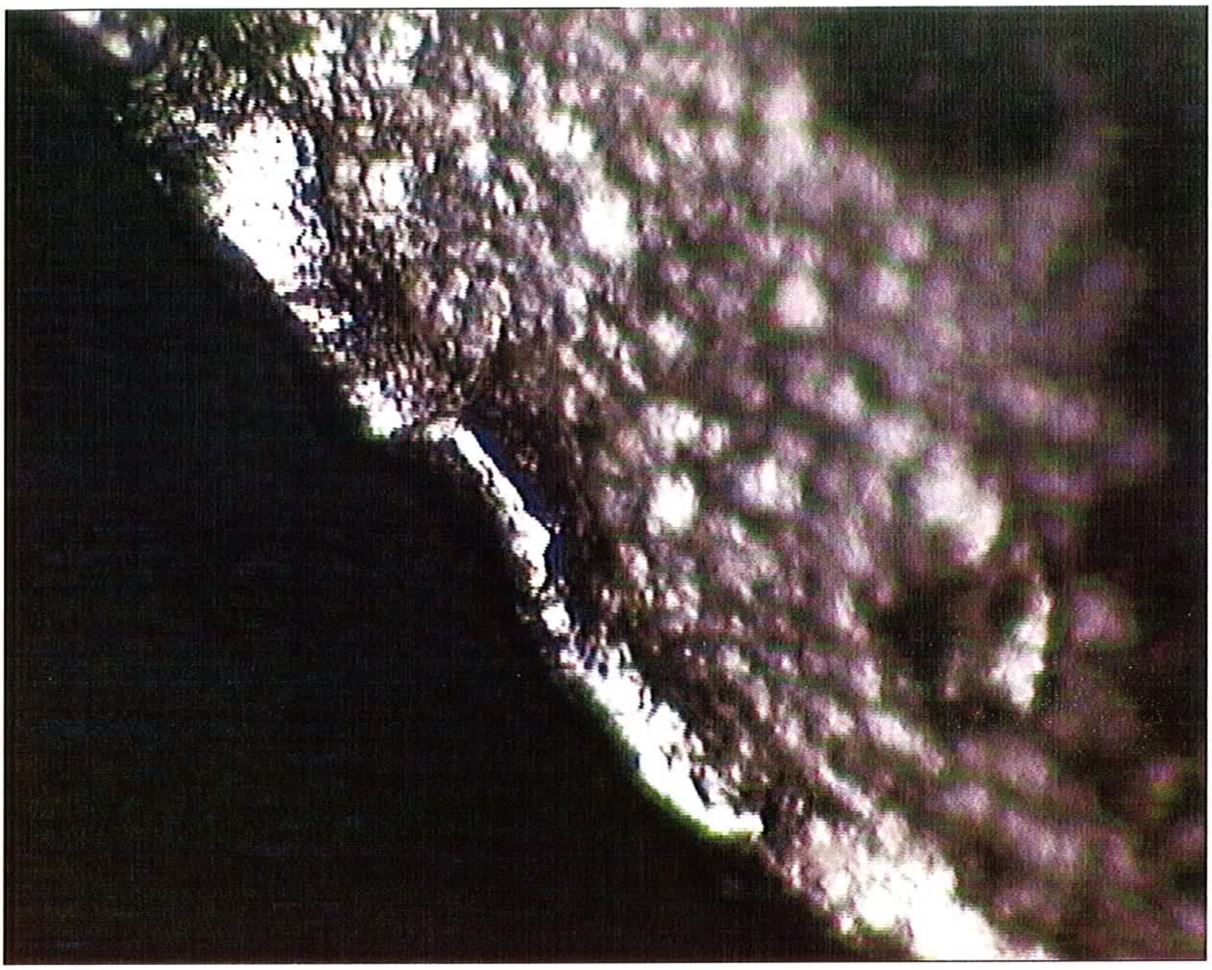


Figure 48. Lip of Unpeened Twist Drill After Use.

(Magnification X 32)

	Unpeened	Peened	Unpeened	Unpeened	Peened	Peened
	Drill	Drill	Drill	Drill	Drill	Drill
	Ra	Ra	Drill Dia.	Hole Dia.	Drill Dia.	Hole Dia.
1	4.28	3.29	10	10.15	10	10.15
2	3.6	3.66	10	10.17	10	10.17
3	6.71	5.05	10	10.21	10	10.17
4	6.61	4.41	10	10.22	10	10.18
5	6.24	4.65	10	10.24	10	10.18
6	6.15	6.08	10	10.24	10	10.18
7	4.2	4.01	10	10.25	10	10.18
8	5.13	4.6	10	10.26	10	10.18
9	4.69	3.86	10	10.26	10	10.18
10	3.98	4.76	10	10.27	10	10.18
11	4.5	4.03	10	10.29	10	10.2
12	4.44	4.25	10	10.29	10	10.2
13	4.37	4.26	10	10.28	10	10.19
14	4.1	4.01	10	10.28	10	10.19
15	5.93	5.8	10	10.28	10	10.19
16	5.83	5.67	10	10.3	10	10.19
17	4.48	4.31	10	10.26	10	10.18
18	5.39	4.63	10	10.27	10	10.15
19	6.36	4.94	10	10.29	10	10.15
20	5.51	4.81	10	10.3	10	10.15
21	5.64	5.41	10	10.3	10	10.15
22	6.46	5.09	10	10.3	10	10.15
23	6.37	5.32	10	10.29	10	10.13
24	6.39	5.31	10	10.32	10	10.15
25	4.69	4.42	10	10.32	10	10.13
26	4.92	4.52	10	10.33	10	10.16
27	4.6	3.87	10	10.32	10	10.16
28	5.64	4.35	10	10.32	10	10.15
29	6.27	5.19	10	10.31	10	10.13
30	5.86	5.27	10	10.34	10	10.14
31	5.88	5.75	10	10.33	10	10.14
32	6.25	5.92	10	10.33	10	10.13
33	6.53	4.8	10	10.33	10	10.11
34	6.18	5.12	10	10.34	10	10.11
35	6.29	4.36	10	10.34	10	10.11
36	5.16	4.62	10	10.34	10	10.11
Sum	195.63	170.4	360	370.27	360	365.7
Mean	5.43	4.73	10	10.29	10	10.16

Table 3: Hole Diameters for Peened and Unpeened Drills

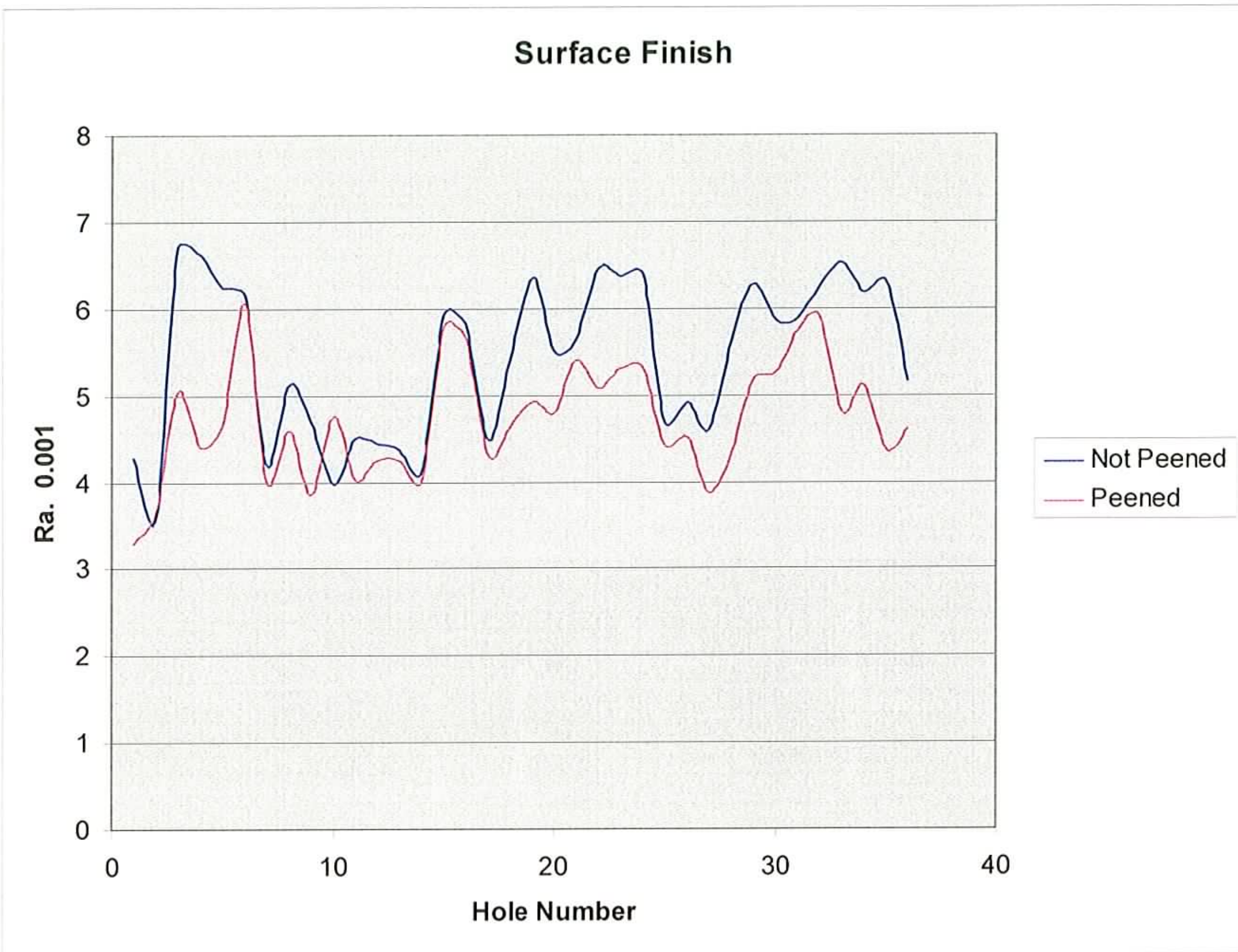
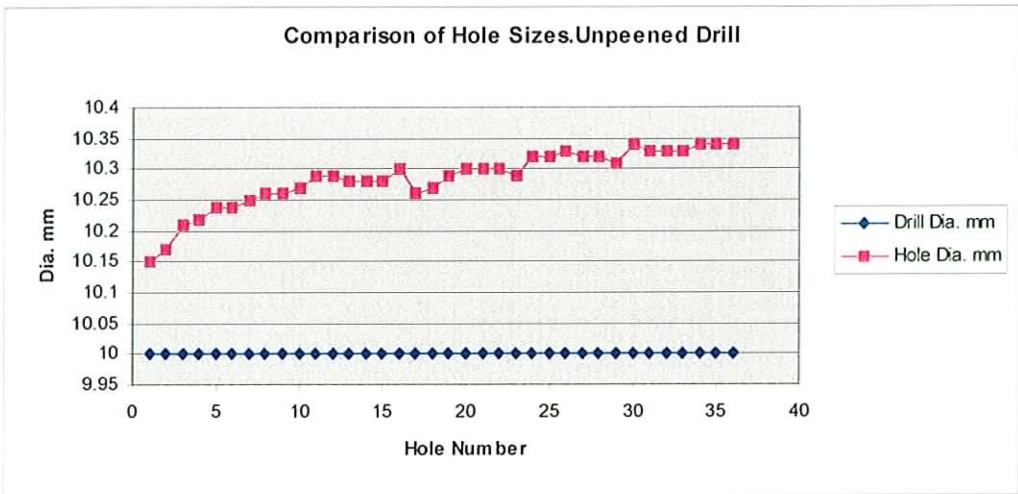
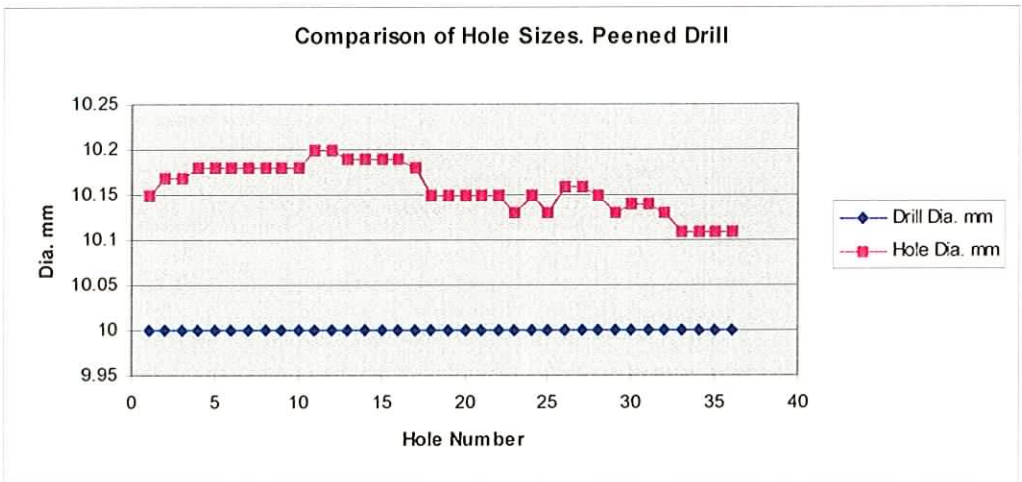


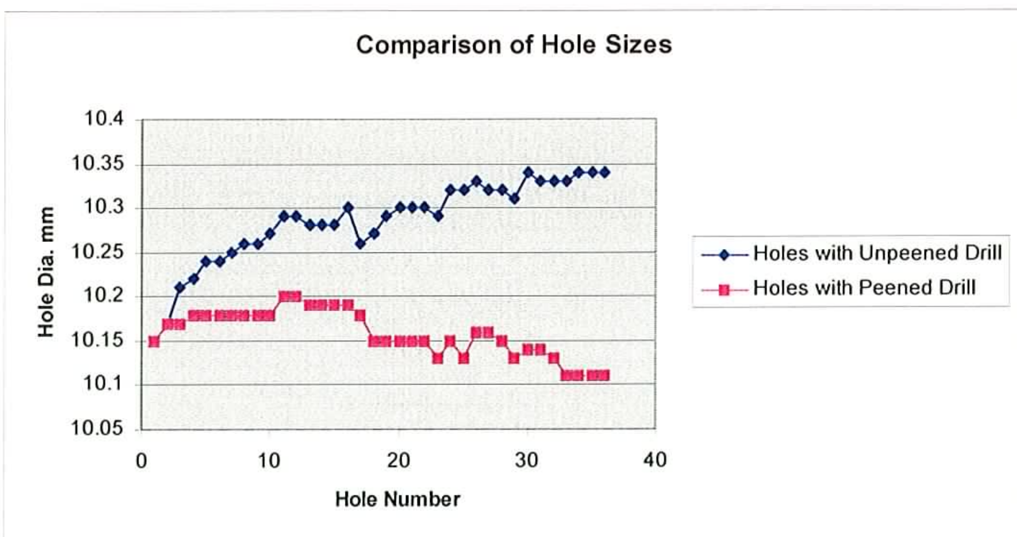
Figure 49. Comparison of Surface Finishes / Ra Values.



A



B



C

Figure 50. Comparison of Hole Diameters.

5.2 Peening of Cutting Tool Tips.

Tungsten carbide inserts for turning tools were subjected to the micro-shot peening process using ceramic shot. A precision shot peening machine, as described in Chapter 4, was used to deliver the shot at high velocity onto the tool insert surface. The peening conditions for this operation are shown in Table 4. The peening conditions were similar to those used for shot peening of twist drills but the linear speed of the nozzle was reduced to 0.6m/sec which had the effect of doubling the the peening time which was used to produce an intensity of 0.5A on an Almen strip.

Variable	Value
Air pressure.	5.5 bar
Nozzle Diameter.	2mm
Nozzle to surface dimension.	50 mm
Angle of impact.	90°.
Cylinder speed.	0.60 m/sec
Increment in y axis.	0.04mm
Coverage.	100%
Intensity.	0.50A (peening time x 2)
Media Type.	Ceramic Shot
Ceramic Shot Specification.	
Chemical composition.	ZrO_2 67%, SiO_2 31%, Other 2%.
Density.	3.85 kg/l
Hardness.	60 Rockwell C
Colour.	White
Media size.	150 microns

Table 4. Operating Conditions for Peening of Carbide Tools.

The surface hardness and the surface roughness of the peened cutting tool was measured and compared with a similar tool that was not peened. Both tools were then used to machine bars of freecutting steel for a sufficient length of time to ensure that tool wear would occur. During the cutting operation a tool force dynamometer was used to measure the tangential force on the tool. Successive cuts were taken with the tools along the diameter of the bar and the tangential force was recorded for each cut. The results for these values are shown in Table 5 and a comparison of cutting forces is shown for peened and unpeened cutting tools in Figure 51.

Cut No.	Cutting Time Seconds	Dynamometer Deflection .001mm Peened Tool	Dynamometer Deflection .001mm Unpeened Tool
1	169	76	83
2	338	76	83
3	507	76	83
4	676	76	83
5	845	76	83
6	1014	79	83
7	1183	79	83
8	1352	79	84
9	1521	79	86
10	1690	81	86
11	1859	81	89
12	2028	81	89
13	2197	81	91
14	2366	84	95
15	2535	86	96

Table 5. Results from Cutting Operations.

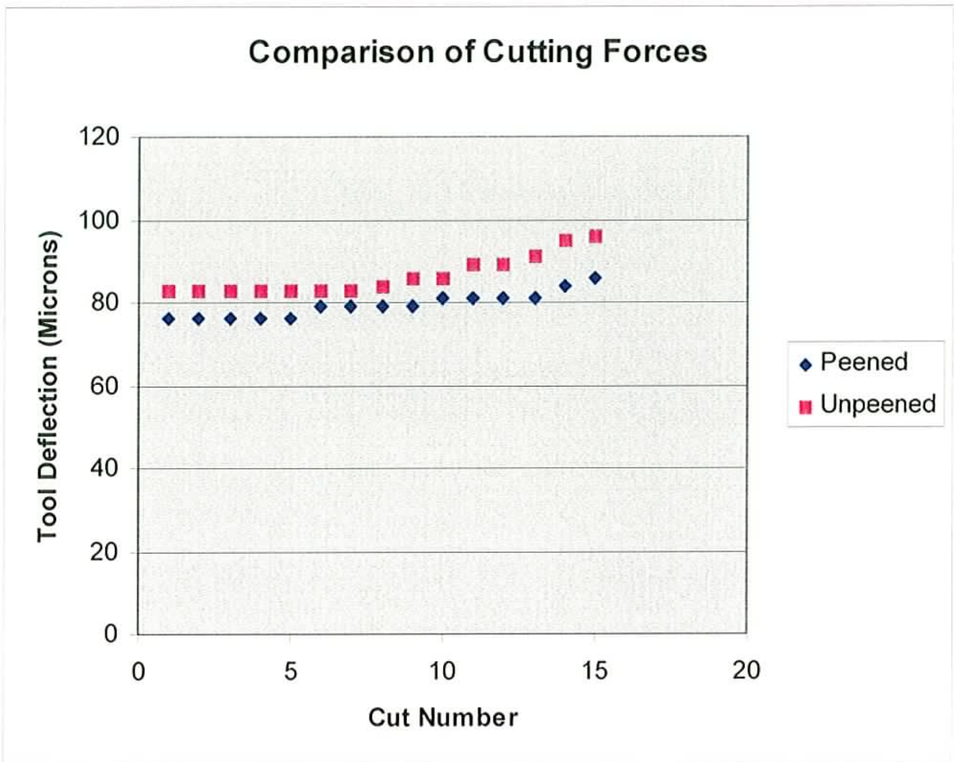


Figure 51. Comparison of Cutting Forces on Peened and Unpeened Carbide Tipped Tools

On completion of the cutting operation both tools were examined for flank wear and cratering of the rake face. The surface roughness of the turned components produced by the peened and unpeened tools was recorded. The results of these tests are shown in Table 6.

	Peened	Unpeened
Hardness	1388 HV	1318 HV
Ra.of Tool Rake Face	0.23 Microns	0.31 Microns
Ra.of Workpiece (30Sec)	2.7	2.8
Ra.of Workpiece (2535Sec)	3.8	6
Flank Wear	90 microns	150 microns

Table 6.Tool and Workpiece Condition

5.3 Peening of Steel Samples.

Three samples of ground flat steel, (1%C), 20mm wide, 60mm long and 8mm thick were micro shot peened. The peening was applied to one half of the flat surface with the other half of the surface being masked to avoid exposure to the shot.

Variable	Value
Air pressure.	5 bar
Nozzle Diameter.	2mm
Nozzle to surface dimension.	50 mm
Angle of impact.	Variable. 90°, 80°, 70°.
Cylinder speed.	0.60 m/sec
Increment in y axis.	0.02mm
Coverage.	120%
Intensity.	0.55A
Media Type.	Ceramic Shot
Ceramic Shot Specification.	
Chemical composition.	ZrO_2 67%, SiO_2 31%, Other 2%.
Density.	3.85 kg/l
Hardness.	60 Rockwell C
Colour.	White
Media size.	150 microns

Table 7. Operating Conditions for Peening of Steel Samples.

The angle of impact was set at different angles for each of the three samples before the start of the peening operation.

Sample 1. Impact angle = 90°

Sample 2. Impact angle = 80°

Sample 3. Impact angle = 70°

After completion of the peening operation the masking element was removed and a surface texture measurement was taken on the unpeened area of each sample. The average Ra value for all three samples was 1.08 microns.

The surface texture of the peened areas was then measured and the following results obtained;

Sample 1. Ra = 2.66 microns.

Sample 2. Ra = 2.95 microns.

Sample 3. Ra = 3.20 microns.

The samples were examined usung a microscope camera and images of the three samples are reproduced in Figures 52, 53 and 54.

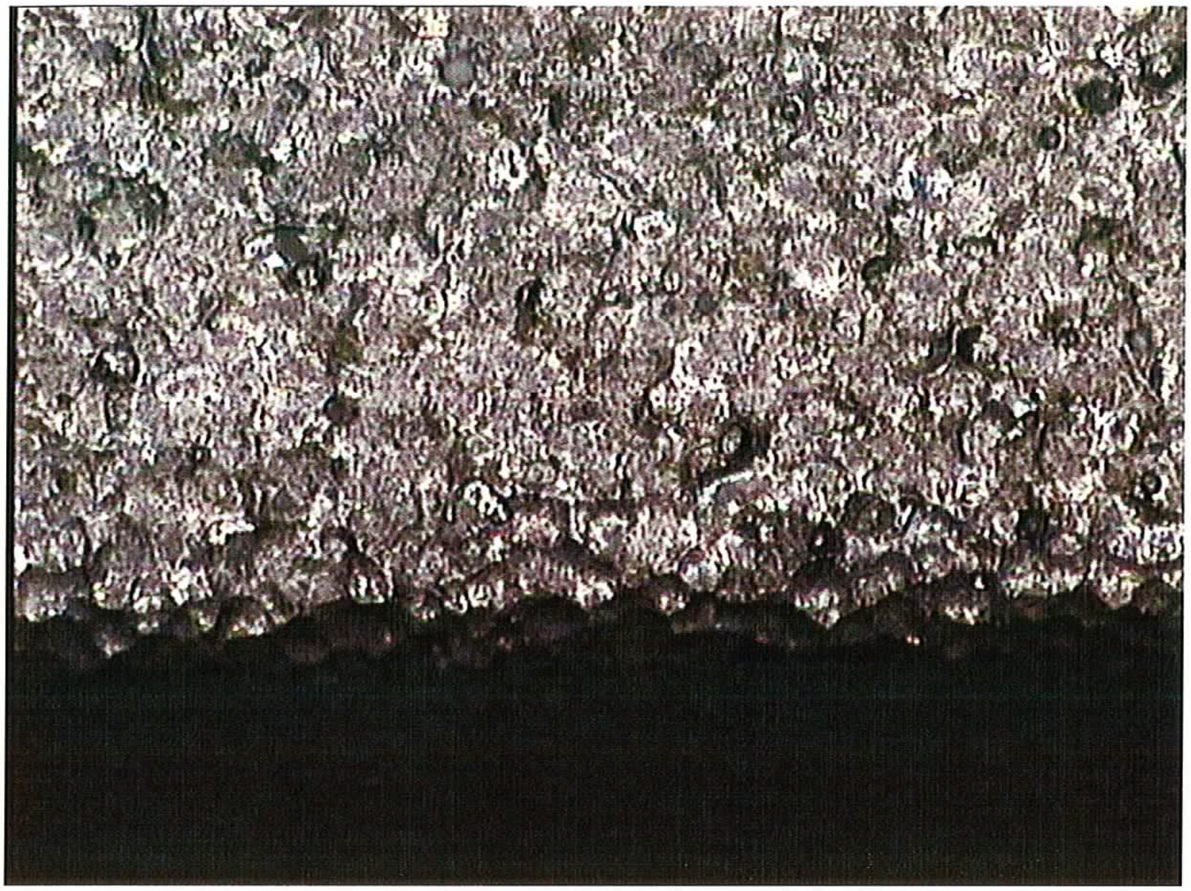


Figure 52. Sample Shot Peened at 90°.

(Magnification X 50)

From the surface texture readings it appears that there is an increased roughness as the angle of impact is decreased. This suggests that there is increased plastic deformation at the material surface as the impact angle is reduced. The microscopic views show regular spherical shaped craters for an impact angle of 90° and slight elongation of the craters for lesser angles. This concurs with known data in shot peening impingement angles [35] [36].

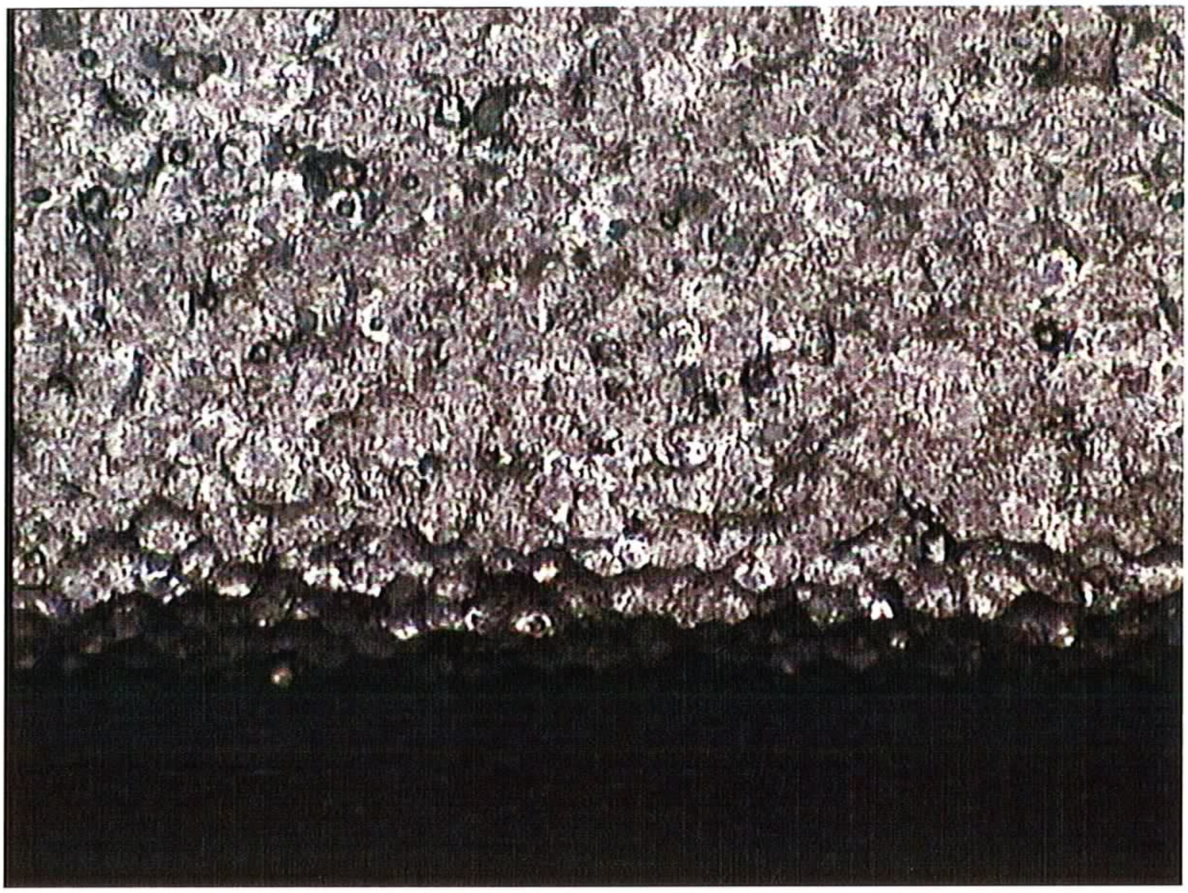


Figure 53. Sample Shot Peened at 80°.

(Magnification X 50)

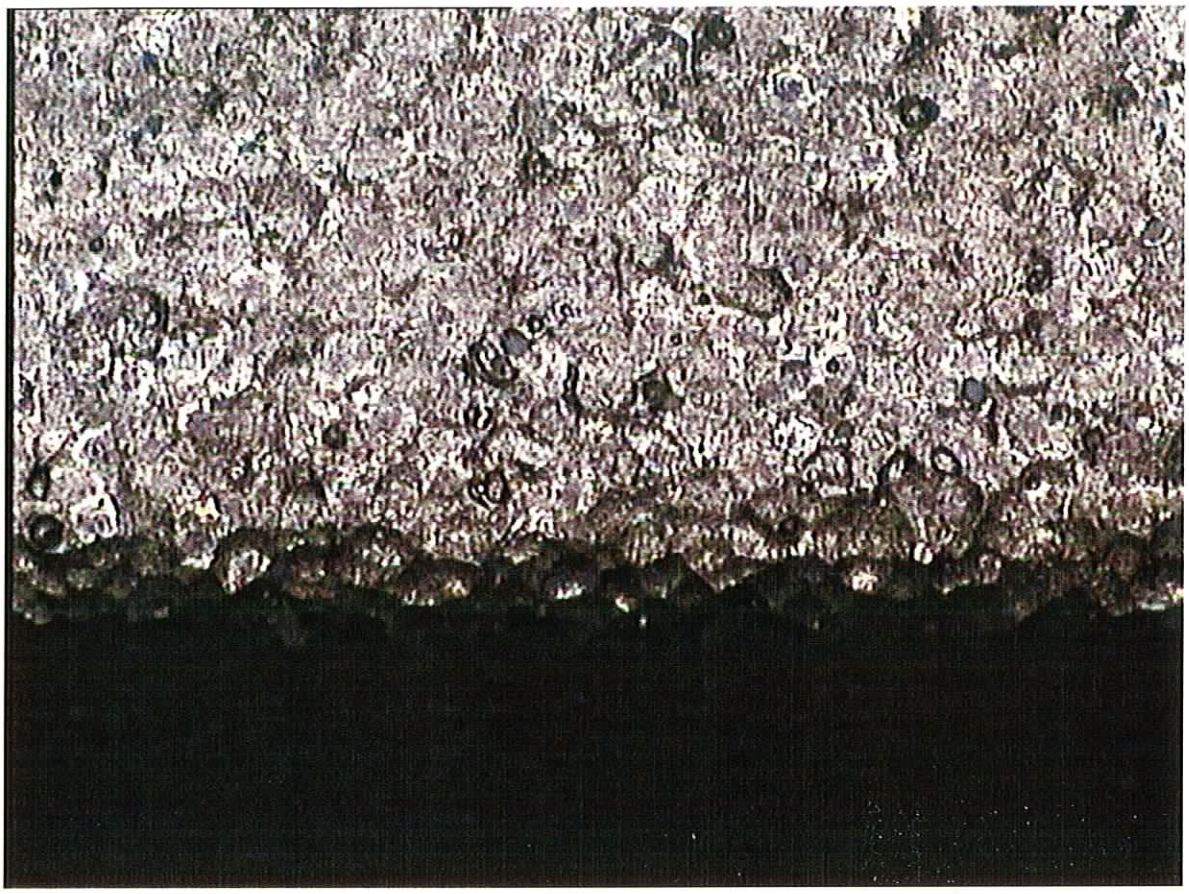


Figure 54. Sample Shot Peened at 70°.

(Magnification X 50)

The junction of the peened and unpeened areas for sample 1 is shown in Figure 55. A scale of 1mm long is shown at the junction. The spherical craters produced by the impact angle of 90° are visible in the right hand section of the image.

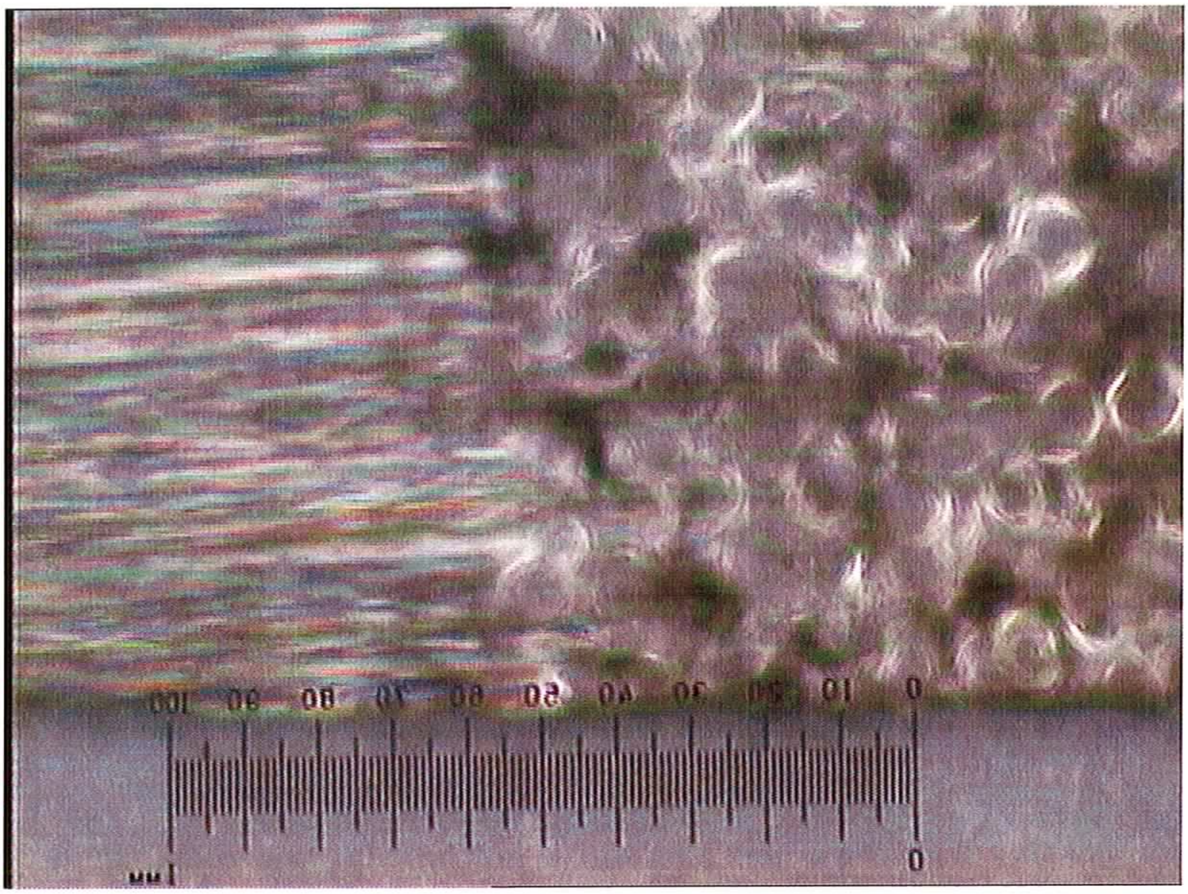


Figure 55. Junction of Peened and Unpeened Areas of Sample.

5.4 Peening of EPDM Rubber.

Three samples of EPDM rubber were subjected to optical profilometry to determine their respective surface roughness. This is a non contact method of assessing surface texture. In practise the surface to be assessed replaces one of the mirrors in a Michelson interferometer. A light beam of short coherence length (typically 1 micron) is split into two parts by a beam splitter so as to illuminate both the surface and a reference mirror. On recombination of the beams at the beamsplitter, interference effects are obtained only if the optical path difference in the interferometer is less than the coherence length. As the mirror is translated parallel to itself, the surface is imaged by a CCD camera and the images are captured and passed to a PC. As the path length of the reference beam changes ,different regions of the test surface meet the coherence condition and the light intensity at the corresponding CCD pixel is modulated. By noting the position of the reference mirror when each pixel is modulated, a profile of the surface can be progressively built up. This technique, which is non contact, covers the whole area of the surface, unlike conventional stylus profilometry which samples straight line planes of a surface. Figure 56 shows an unpeened sample of EPDM rubber. The surface roughness values for the samples were as follows:

Sample 1. 1.32 microns.
Sample 2. 0.60 microns.
Sample 3. 0.75 microns.

The samples were then micro-shot peened using a ceramic bead as described in section 4.5. Figure 57 shows the same sample after micro-shot peening. The surface texture was again assessed for the three samples and the following results were obtained;

Sample 1. 0.78 microns.

Sample 2. 0.40 microns.

Sample 3. 0.49 microns.

These results show that the surface texture of EPDM rubber can be improved by the application of shot peening. This may have beneficial applications in medical and hygiene fields where surface texture can be an important factor when reducing or eliminating bacteria by liquid washing methods.

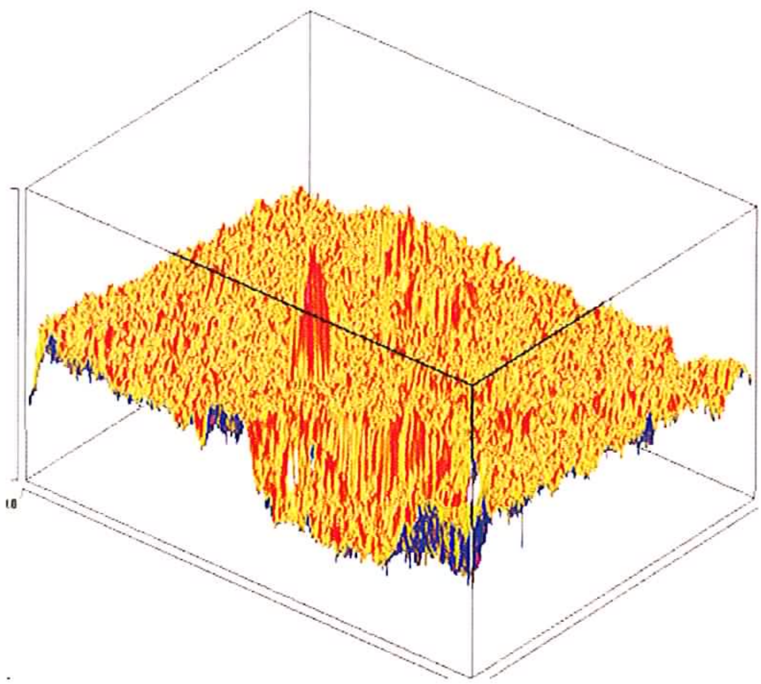


Figure 56. Surface Profile of Unpeened Rubber Sample

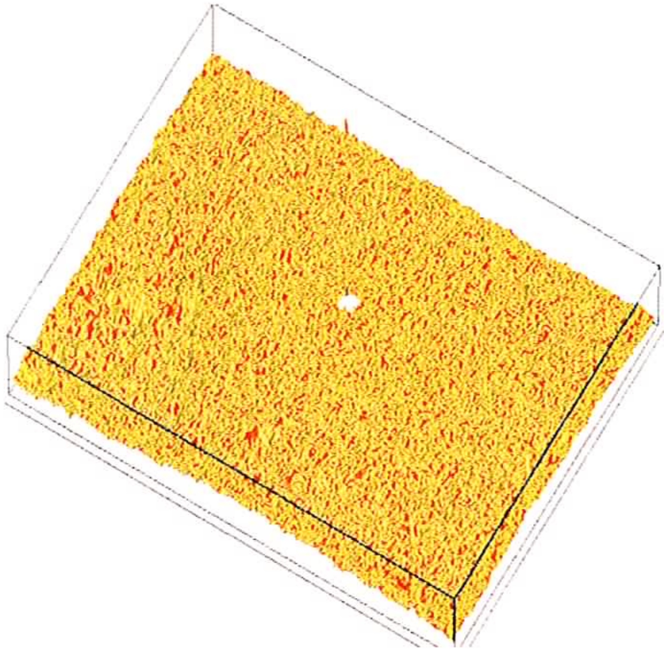


Figure 57. Surface Profile of Peened Rubber Sample.

Ten strips of the EPDM rubber were then subjected to tensile tests. The loads were applied slowly and the % elongation was recorded for each load. The samples were identical in dimension and were tested to destruction. Five of the samples were as supplied and five were micro-shot peened. Table 6 shows the load versus % elongation for one of the peened and one of the unpeened samples. Figure 58 shows the comparative tensile strengths for peened and unpeened samples. The tensile tests showed that there was no improvement in tensile strength but it is significant that there was no decrease in strength for the peened sample although some material was removed as shown in the surface texture tests.

Unpeened Load	Unpeened % Elongation	Peened Load	Peened % Elongation
1.3387	4.302	0.37905	1.5143
8.1883	25.56	0.37779	1.5946
11.515	43.941	9.0939	20.708
14.842	61.489	12.223	40.395
17.585	78.807	14.978	57.825
20.207	96.046	17.655	75.006
22.828	113.24	20.332	92.098
25.45	130.43	22.899	109.15
28.071	147.62	25.118	126.2
30.693	164.81	27.337	143.24
33.315	181.99	29.555	160.28
35.936	199.17	31.774	177.32
39.269	216.35	33.993	194.36
42.705	233.54	36.283	211.39
46.141	250.72	39.162	228.43
49.577	267.9	42.041	245.47
53.449	285.09	44.92	262.5
57.48	302.27	47.856	279.54
61.51	319.45	51.608	296.58
66.367	336.63	55.359	313.62
71.326	353.82	59.11	330.65
76.285	371	62.944	347.69
81.244	388.18	67.642	364.73
86.203	405.37	72.34	381.76
93.327	422.55	77.037	398.8
99.144	439.73	81.735	415.84
104.96	456.91	86.778	432.87
110.78	474.1	92.358	449.91
116.59	491.28	97.938	466.95
122.65	508.46	103.52	483.99
128.95	525.65	109.1	501.02
135.26	542.83	114.76	518.06
141.56	560.01	121.14	535.1
147.92	577.2	127.52	552.13
154.32	594.38	133.9	569.17
160.92	611.56	140.27	586.21
167.59	628.74	146.65	603.25
174.27	645.93	153.03	620.28
180.94	663.11	159.4	637.32
187.62	680.29	165.78	654.36
194.29	697.48	172.16	671.39
200.74	714.66	178.54	688.43
207.18	731.84	184.91	705.47
213.63	749.02	191.26	722.5
220.07	766.21	197.55	739.54
226.52	783.39	203.83	756.58
232.96	800.57	210.11	773.62

Table 6. Tensile Test of Peened and Unpeened EPDM.

Unpeened Load	Unpeened % Elongation	Peened Load	Peened % Elongation
239.31	817.75	216.4	790.65
245.34	834.93	222.68	807.69
251.38	852.12	228.96	824.73
257.42	869.3	235.25	841.76
263.45	886.48	241.53	858.8
269.49	903.66	247.81	875.84
275.48	920.85	253.86	892.87
281.03	938.03	259.7	909.91
286.59	955.21	265.53	926.95
292.14	972.4	271.36	943.99
297.7	989.58	277.2	961.02
303	1006.8	283.03	978.06
307.75	1023.9	288.56	995.1
312.78	1041.1	293.85	1012.1
317.81	1058.3	299.12	1029.2
322.84	1075.5	304.39	1046.2
327.86	1092.7	309.66	1063.2
332.89	1109.9	314.93	1080.3
337.92	1127	320.33	1097.3
342.59	1144.2	325.57	1114.4
347.25	1161.4	329.91	1131.4
351.9	1178.6	334.65	1148.4
356.55	1195.8	339.51	1165.5
361.21	1213	344.36	1182.5
366.13	1230.1	349.21	1199.5
371.84	1247.3	355.06	1216.6
377.54	1264.5	361.05	1233.6
383.25	1281.7	367.04	1250.7
388.96	1298.9	373.03	1267.7
394.67	1316.1	379.02	1284.7
400.38	1333.2	384.78	1301.8
405.76	1350.4	390.08	1318.8
410.92	1367.6	395.38	1335.8
416.09	1384.8	400.68	1352.9
420.67	1402	405.61	1369.9
425.22	1419.2	410.32	1386.9
429.77	1436.3	415.03	1404
434.32	1453.5	419.73	1421
438.87	1470.7	424.44	1438.1
442.42	1487.9	428.75	1455.1
446.32	1505.1	432.68	1472.1
450.22	1522.3	436.62	1489.1
454.12	1539.4	440.55	1506.2
458.02	1556.6	444.49	1523.2
461.92	1573.8	448.42	1540.3
465.82	1591	452.32	1557.3
469.29	1608.2	455.64	1574.3

Table 6. Tensile Test of Peened and Unpeened EPDM.

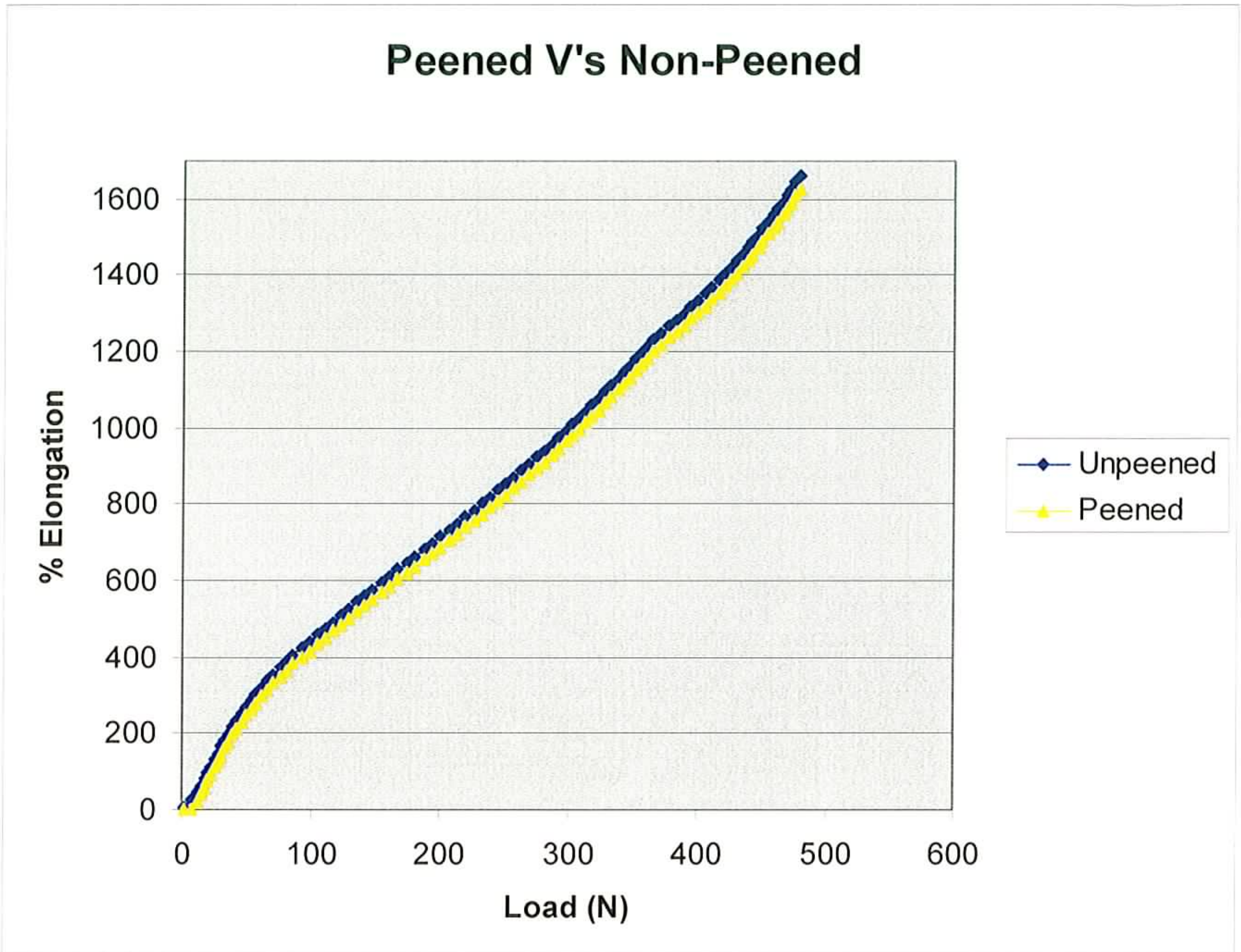


Figure 58. Comparison of Tensile Test on Peened and Unpeened Rubber Sample.

Ten circular discs of EPDM rubber were prepared and were then tested for fatigue strength. Five of the discs were shot peened on both sides and five were as supplied. Each disc was clamped between two steel flanges so that a leak proof seal was formed. Pressure was then applied to one side of the disc by means of a hydraulic cylinder. This caused the disc to inflate to form a balloon like bubble thereby creating a biaxial stress in the rubber. The maximum pressure developed for this particular test was 4 bar. The pressure was then released allowing the bubble to deflate. This cycle was repeated continuously until rupture of the material occurred. Single shot inflations to a pressure sufficient to cause rupture tend to produce a star or cloverleaf pattern at the rupture site as shown in Figure 59 [40] [41]. During these tests, rupture due to fatigue was in the form of a single straight scar running through the bubble pole as shown in Figure 60 . Tests have shown that fracture emanates from the pole of the bubble where maximum stress occurs [40][41]. The average number of cycles to failure for the unpeened samples was 2317 while the average for the peened samples was 2384. This figure is not considered significant as the difference is less than failure cycles for similar samples [40]. This would suggest that shot peening of EPDM does not improve the fatigue life of the material.

Figure 59. Failure pattern of EPDM disc due to single inflation.

(Magnification X 1)

Figure 60. Failure pattern of EPDM disc due to fatigue.

(Magnification X 1)

CHAPTER 6

Conclusions.

6.0 Conclusions

Extensive work by many researchers has established the value of shot peening as a process in the enhancement of material properties particularly in the areas of component failure due to fatigue [13-16]. This in turn has enabled smaller and therefore lighter components to be used in many applications without compromising the reliability or safety of the design. The value of this development is particularly important in the automotive and aviation industry where safety and weight saving are important considerations. The reduction in component weight also provides significant savings in the fuel running costs.

The current research was mainly based on experiments using micro shot peening techniques to determine the effects of the process on the performance of hardened cutting tools. Micro shot peening was also carried out on non metallic materials to establish if any improvements could be achieved by the application of this process.

Experimental work on carbide tips for turning tools clearly shows that the performance of the tip can be improved by the application of micro shot peening. In the tests the shot peened tips showed reduced cutting forces resulting in less power consumption per unit volume of material removed. The useful working life of the tip was extended before critical wear occurred to the flank and rake faces. An improvement of the surface finish of the machined component was also observed for the operations carried out using the shot peened tip.

The shot peening process was also applied to high speed steel (h.s.s.) twist drills. The performance of the peened drills was then compared to the performance of standard high speed steel drills. In these tests the peened drills produced more accurate diameter holes with a superior surface finish than the non peened drills. Tests were performed on both sets of drills using higher speeds and feed rates than normal. These conditions were designed to produce rapid wear rates of the drills. On completion of the tests the cutting edges were examined using a microscope camera. The unpeened drills showed extensive lip damage while the peened drills remained relatively undamaged. This would seem to indicate that the peening process imparted additional toughness to the drill cutting edge which helped it withstand the wear caused by abusive drilling conditions.

Samples of EPDM rubber that were shot peened under controlled conditions showed a significant improvement in the surface texture. However tensile and fatigue tests on the samples resulted in almost identical results for the peened and unpeened samples.

6.1 Future Work.

The research carried out in this thesis on high speed twist drills produced some positive results and further study and experimentation in this area would prove worthwhile. The application of peening to twist drills at the manufacturing stage would also be recommended as control of the peening nozzle position relative to the surface of the drill could be more closely controlled. This would result in more consistent improvements to the drills performance.

Shot peening of corrosion resistant surfaces on base materials is also worthy of study. The porosity of the surface can be altered by peening and hence the corrosion resistance could be improved.

Further work on shot peening of non metallic materials is also recommended. This could also explore the applications of the improved surface texture on these materials due to the process.

6.2 Papers Published.

A number of papers were produced during the period of this study. These include one published journal paper and two conference papers.

Published Papers.

Micro Shot Blasting of Machine Tools for Improving Surface Finish and Reducing Cutting Forces in Manufacturing, Materials and Design 26 (2005).

Conference papers.

Micro Shot Peening of Coated Cutting Tool Tips, M T 2002, DIT, Dublin.

Micro Shot Peening of Twist Drills and Their Machining Performance of Mild Steel. Matrib 2004, Croation Society of Materials and Tribology. Croatia.

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Appendix 1

Programmable Logic Controller PLC

The controller for the shot peening process was a Sprecher and Schuh PLC and the program shown below was written to allow parameters of the process to be easily modified.

Program

LC0000	Store	X001	
LC0001	Out	Y001	
LC0002	Store	X002	
LC0003	Store	X001	
LC0004	TMR	V001	0001
LC0005	Out	C001	
LC0006	Store	X002	
LC0007	AND NOT	C001	
LC0008	Out	Y005	
LC0009	Store	X002	
LC0010	End		

Appendix 2

CNC Program for Peck Drilling

```
Operation List    POST: Deckel dialog 4 - braye
-----------------------------------------------
OP 1   PECK HOLES   TOOL 33   DRILL - 10MM
     TOOL DIAMETER 10, HOLE DIAMETERS 10
     Feed Distance: 1462   Time for OP 1: 30m 58s
-----------------------------------------------
Total Feed Distance ......................... 1462
Tool Change Time .......................... 0m 10s
Total Time .............................. 31m 08s
-----------------------------------------------
Material: Mild Steel Roughing
Use Emulsion Coolant
-----------------------------------------------
START
'(DRILLING)
&%0001


%
(&%0001/000000"DRILLING)
'(OP 1   PECK HOLES   TOOL 33   DRILL - 10MM)
'(TOOL DIAMETER 10, HOLE DIAMETERS 10)
N1 G0 X-50. Y-50. Z100.
N2 G17 T33
N3 G0 Z10.
N4 G0 X12.5 Y12.5 S+2500
N5 G0 X12.5 Y12.5 Z10.
N6 G83 F50 S+2500 Z-31. Z-2. Z-1. Z0. Z9.
N7 G0 X12.5 Y27.5 Z10.
N8 G83 F50 S+2500 Z-31. Z-2. Z-1. Z0. Z9.
N9 G0 X12.5 Y42.5 Z10.
N10 G83 F50 S+2500 Z-31. Z-2. Z-1. Z0. Z9.
N11 G0 X12.5 Y57.5 Z10.
N12 G83 F50 S+2500 Z-31. Z-2. Z-1. Z0. Z9.
N13 G0 X12.5 Y72.5 Z10.
N14 G83 F50 S+2500 Z-31. Z-2. Z-1. Z0. Z9.
```

```
N15 G0 X12.5 Y87.5 Z10.
N16 G83 F50 S+2500 Z-31. Z-2. Z-1. Z0. Z9.
N17 G0 X27.5 Y12.5 Z10.
N18 G83 F50 S+2500 Z-31. Z-2. Z-1. Z0. Z9.
N19 G0 X27.5 Y27.5 Z10.
N20 G83 F50 S+2500 Z-31. Z-2. Z-1. Z0. Z9.
N21 G0 X27.5 Y42.5 Z10.
N22 G83 F50 S+2500 Z-31. Z-2. Z-1. Z0. Z9.
N23 G0 X27.5 Y57.5 Z10.
N24 G83 F50 S+2500 Z-31. Z-2. Z-1. Z0. Z9.
N25 G0 X27.5 Y72.5 Z10.
N26 G83 F50 S+2500 Z-31. Z-2. Z-1. Z0. Z9.
N27 G0 X27.5 Y87.5 Z10.
N28 G83 F50 S+2500 Z-31. Z-2. Z-1. Z0. Z9.
N29 G0 X42.5 Y12.5 Z10.
N30 G83 F50 S+2500 Z-31. Z-2. Z-1. Z0. Z9.
N31 G0 X42.5 Y27.5 Z10.
N32 G83 F50 S+2500 Z-31. Z-2. Z-1. Z0. Z9.
N33 G0 X42.5 Y42.5 Z10.
N34 G83 F50 S+2500 Z-31. Z-2. Z-1. Z0. Z9.
N35 G0 X42.5 Y57.5 Z10.
N36 G83 F50 S+2500 Z-31. Z-2. Z-1. Z0. Z9.
N37 G0 X42.5 Y72.5 Z10.
N38 G83 F50 S+2500 Z-31. Z-2. Z-1. Z0. Z9.
N39 G0 X42.5 Y87.5 Z10.
N40 G83 F50 S+2500 Z-31. Z-2. Z-1. Z0. Z9.
N41 G0 X57.5 Y12.5 Z10.
N42 G83 F50 S+2500 Z-31. Z-2. Z-1. Z0. Z9.
N43 G0 X57.5 Y27.5 Z10.
N44 G83 F50 S+2500 Z-31. Z-2. Z-1. Z0. Z9.
N45 G0 X57.5 Y42.5 Z10.
N46 G83 F50 S+2500 Z-31. Z-2. Z-1. Z0. Z9.
N47 G0 X57.5 Y57.5 Z10.
N48 G83 F50 S+2500 Z-31. Z-2. Z-1. Z0. Z9.
N49 G0 X57.5 Y72.5 Z10.
N50 G83 F50 S+2500 Z-31. Z-2. Z-1. Z0. Z9.
N51 G0 X57.5 Y87.5 Z10.
N52 G83 F50 S+2500 Z-31. Z-2. Z-1. Z0. Z9.
N53 G0 X72.5 Y12.5 Z10.
N54 G83 F50 S+2500 Z-31. Z-2. Z-1. Z0. Z9.
N55 G0 X72.5 Y27.5 Z10.
N56 G83 F50 S+2500 Z-31. Z-2. Z-1. Z0. Z9.
N57 G0 X72.5 Y42.5 Z10.
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N58 G83 F50 S+2500 Z-31. Z-2. Z-1. Z0. Z9.
N59 G0 X72.5 Y57.5 Z10.
N60 G83 F50 S+2500 Z-31. Z-2. Z-1. Z0. Z9.
N61 G0 X72.5 Y72.5 Z10.
N62 G83 F50 S+2500 Z-31. Z-2. Z-1. Z0. Z9.
N63 G0 X72.5 Y87.5 Z10.
N64 G83 F50 S+2500 Z-31. Z-2. Z-1. Z0. Z9.
N65 G0 X87.5 Y12.5 Z10.
N66 G83 F50 S+2500 Z-31. Z-2. Z-1. Z0. Z9.
N67 G0 X87.5 Y27.5 Z10.
N68 G83 F50 S+2500 Z-31. Z-2. Z-1. Z0. Z9.
N69 G0 X87.5 Y42.5 Z10.
N70 G83 F50 S+2500 Z-31. Z-2. Z-1. Z0. Z9.
N71 G0 X87.5 Y57.5 Z10.
N72 G83 F50 S+2500 Z-31. Z-2. Z-1. Z0. Z9.
N73 G0 X87.5 Y72.5 Z10.
N74 G83 F50 S+2500 Z-31. Z-2. Z-1. Z0. Z9.
N75 G0 X87.5 Y87.5 Z10.
N76 G83 F50 S+2500 Z-31. Z-2. Z-1. Z0. Z9.
N77 (CYCLE END)
N78 G0 Z100 M30
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Appendix 3

Shot Peening Standards

AMS 2430

Form: This specification covers the engineering requirements for peening surfaces of parts by impingement of metallic shot, glass beads, or ceramic shot.
Applications: To induce residual compressive stress into surface layers of parts, thereby increasing fatigue strength and resistance to stress-corrosion cracking.

AMS 2431/7

This specification, in conjunction with the general requirements covered in AMS 2431, established the requirements for ceramic shot, for peening of metal parts.

AMS 2432

This specification established the engineering requirements for computer monitored peening of surfaces of parts. Application: This procedure has been used typically to induce, through cold working, a surface layer that is residually stressed in compression thereby enhancing fatigue performance and resistance to stress corrosion cracking, corrosion fatigue, fretting fatigue, spalling and galling, and to provide a means by which the shot peening process can be performed on parts which rely on the benefits provided by shot peening in order to satisfy material component design, but usage is not limited to such applications. Shot peening in conformance with this specification requires that locations of intensity verification (Almen strip locations) be shown on the drawing. Processes such as tumbling of parts in peening, slurry peening, peen forming and straightening, peening for prevention of intergranular corrosion, and peening to produce a surface texture are recognized but their requirements are not covered.

MIL-P-81985

This specification covers procedures and requirements for dry peening the surfaces of metals by impingement of metallic shot or glass beads for the purpose of increasing the fatigue strength of and resistance to stress corrosion cracking by inducing residual compressive stresses in specified surfaces,

AMS 2431

This specification establishes general requirements for the media to be used in controlled shot peening of metal parts.

SAE J443

This SAE *Recommended Practice* provides uniform procedures for using the standard shot peening test strips reported in SAE Standard J442, Test Strip, Holder and Gage for Shot Peening. Standard test strips are used to control repeatability of the shot peening machine operations, and to specify a desired result on a part. It is recommended that the standard test strip A be used for intensities that produce arc heights of 6A to 24A. For intensities below 6A, the standard N strip is recommended. Intensities above 24A, the standard C strip is recommended. Shot peening is intended to induce surface compressive stresses in metal parts for the purpose of improving resistance to fatigue and stress corrosion cracking. Springs, axles and aircraft landing gears are typical examples of such parts. To have the desired effect, shot peening requires that specified intensity and coverage be achieved on critical areas, where the high tension stresses or stress ranges are most likely to cause fatigue or stress corrosion failures in service. Actual experience with service failures or fatigue tests may sometimes be required to discover or confirm the location of areas subject to critical stressing, as a result of service, design and/or manufacturing conditions.

SAE J1830

This specification covers characteristics for chemistry, microstructure, density, hardness, size, shape, and appearance of zirconium oxide based ceramic shot, suitable for peening surface parts by impingement.